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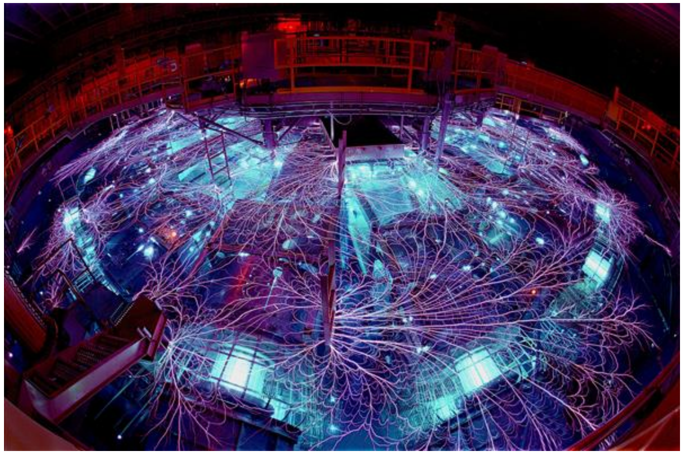

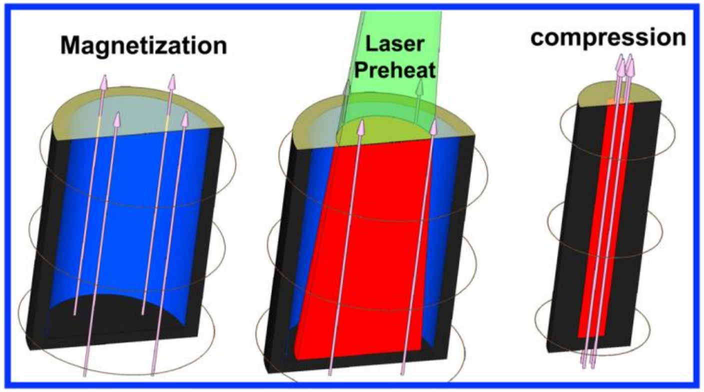

Magnetized Liner Inertial Fusion on the 100-ns Z facility and prospects for a "breakeven" experiment

Daniel Sinars

Sandia National Laboratories

ARPA-E Workshop,

October 29-30, 2013 Berkeley, CA

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Many groups seek to use magnetic fields to relax fusion requirements in pulsed inertial systems. Data remain scarce, but appear promising—can we move the needle on this?

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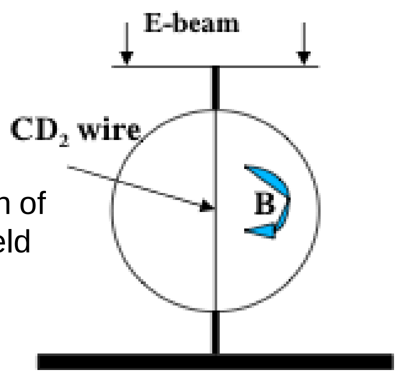
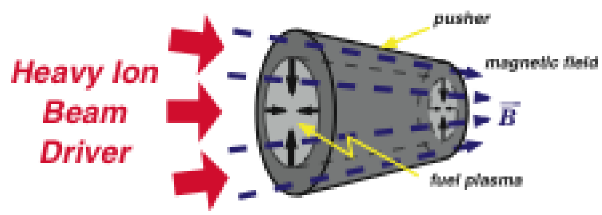
SNL Phi Target

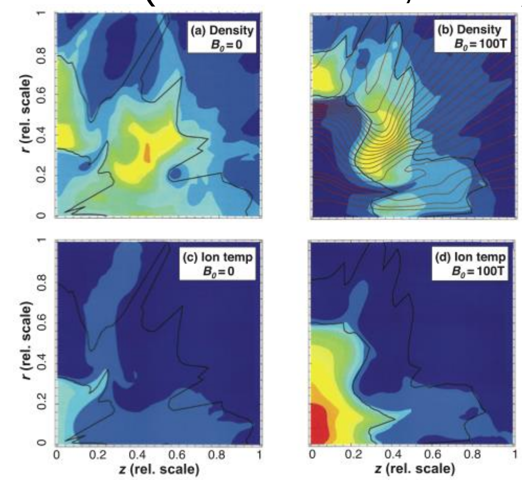


1982 Demonstration of enhanced fusion yield with magnetization (~1e6 DD yield)

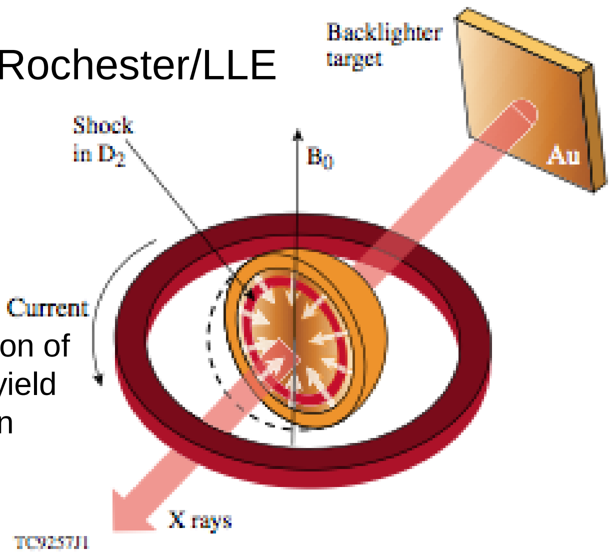
Max Planck/ITEP



LLNL (Perkins *et al.*, 2013)



University of Rochester/LLE



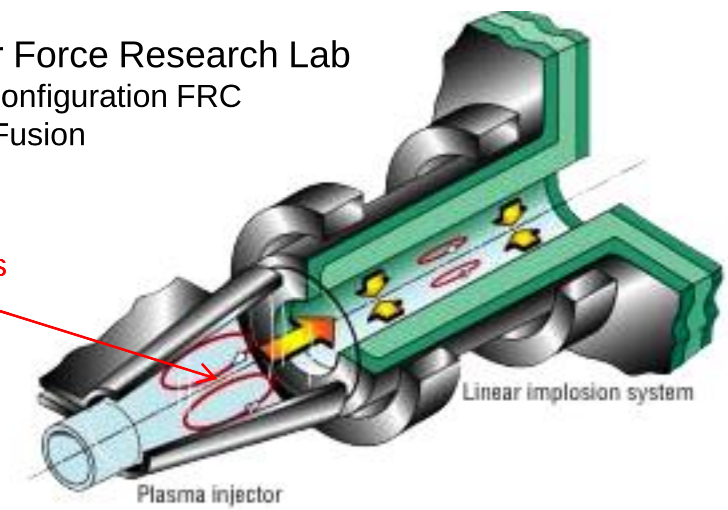
2011 Demonstration of enhanced fusion yield with magnetization (~5e9 DD yield)

P.Y. Chang *et al.*, Phys. Rev. Lett. (2011).

Los Alamos/Air Force Research Lab

Field Reversed Configuration FRC
Magnetic Target Fusion
Shiva Star

closed field lines
FRC



and many more groups besides these…

Magnetized Liner Inertial Fusion (MagLIF)* on the Sandia Z facility is one approach to realizing scientific breakeven within three years and would demonstrate value of fuel magnetization

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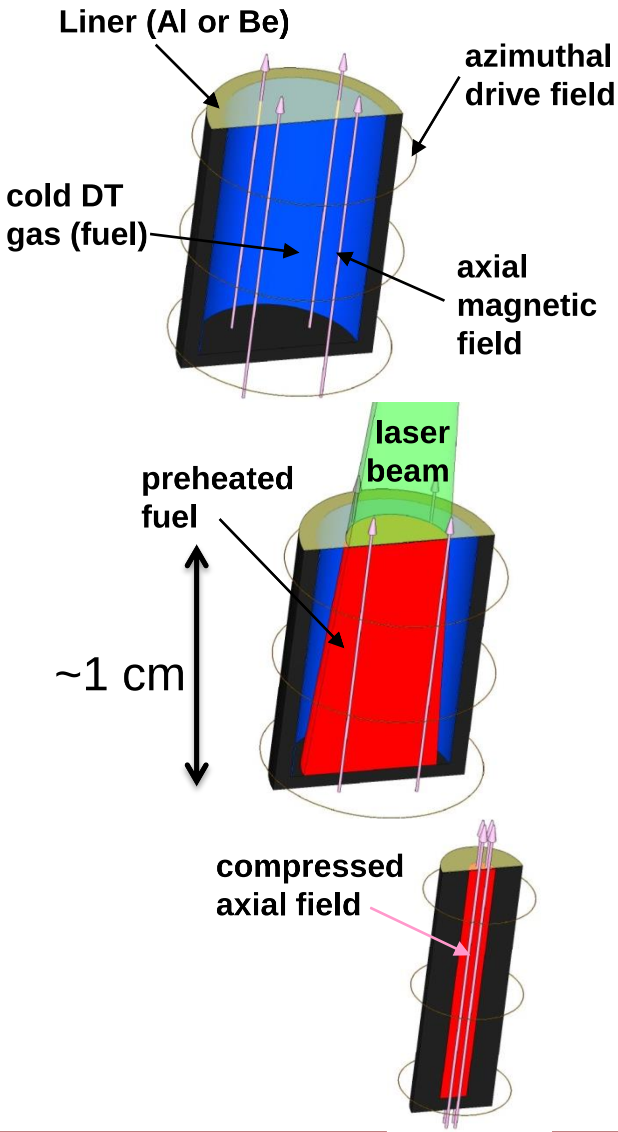

- An initial 30 T axial magnetic field is applied
  - Inhibits thermal conduction losses
  - May help stabilize implosion at late times
- During the ~100 ns implosion, the fuel is heated using the Z-Beamlet laser (about 6 kJ in designs)
  - Preheating to ~300 eV reduces the compression needed to obtain fusion temperatures to 23 on Z
  - Preheating reduces the implosion velocity needed to ~100 km/s, allowing us to use thick liners that are more robust against instabilities
- ~50-250 kJ energy in fuel; 0.2-1.4% of capacitor bank
- Stagnation pressure required is ~5 Gbar
- Gain = 1 may be possible on Z using DT (fusion yield = energy into fusion fuel, also called "scientific breakeven")
  Early experiments would use DD fuel

*S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010). S.A. Slutz and R.A. Vesey, Phys. Rev. Lett. (2012).

We are using the Z pulsed-power facility to develop MagLIF—significant progress has been in the past several years and we expect our first integrated experiments in 2013 (note ICF is only 25% of Z program)

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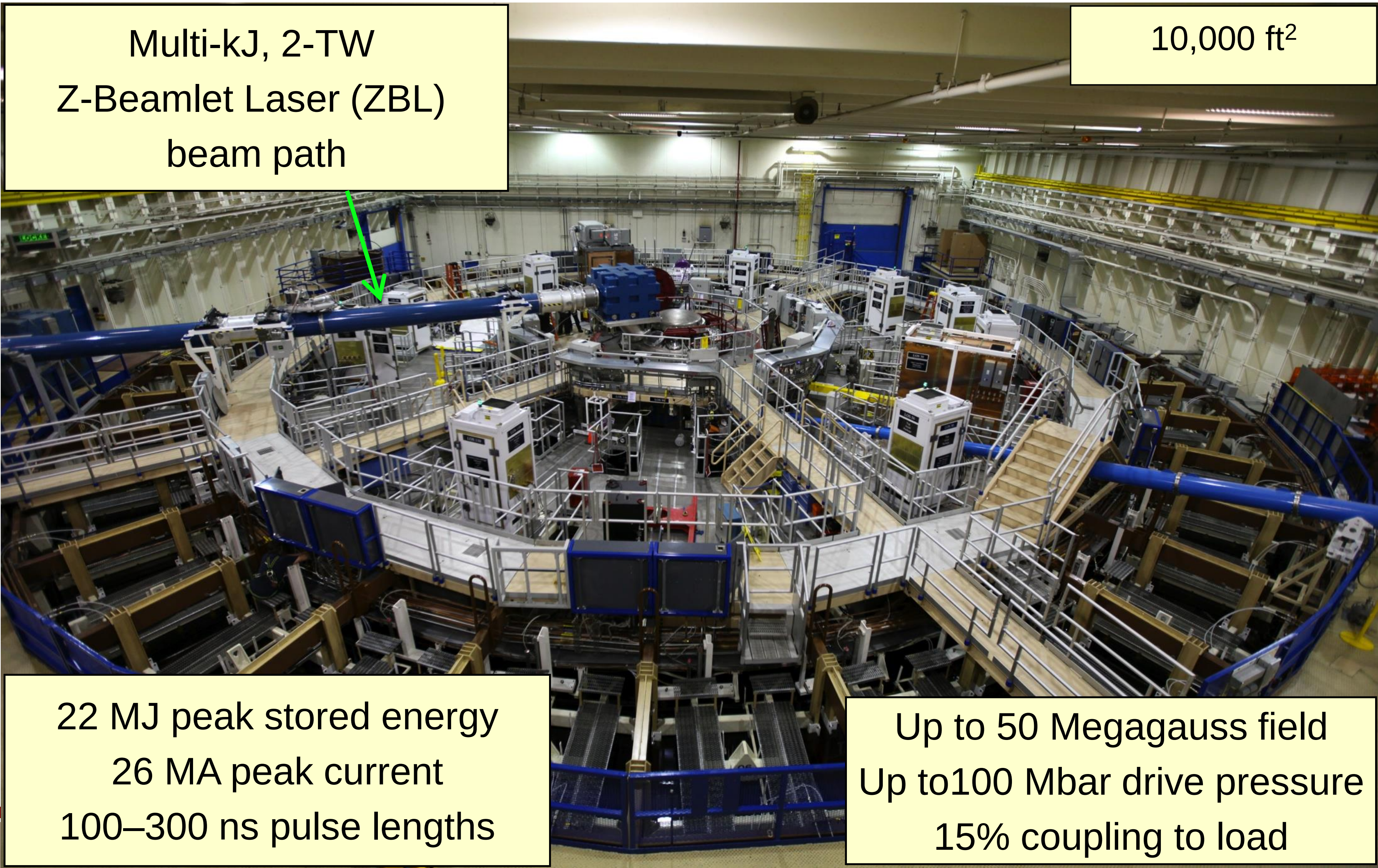
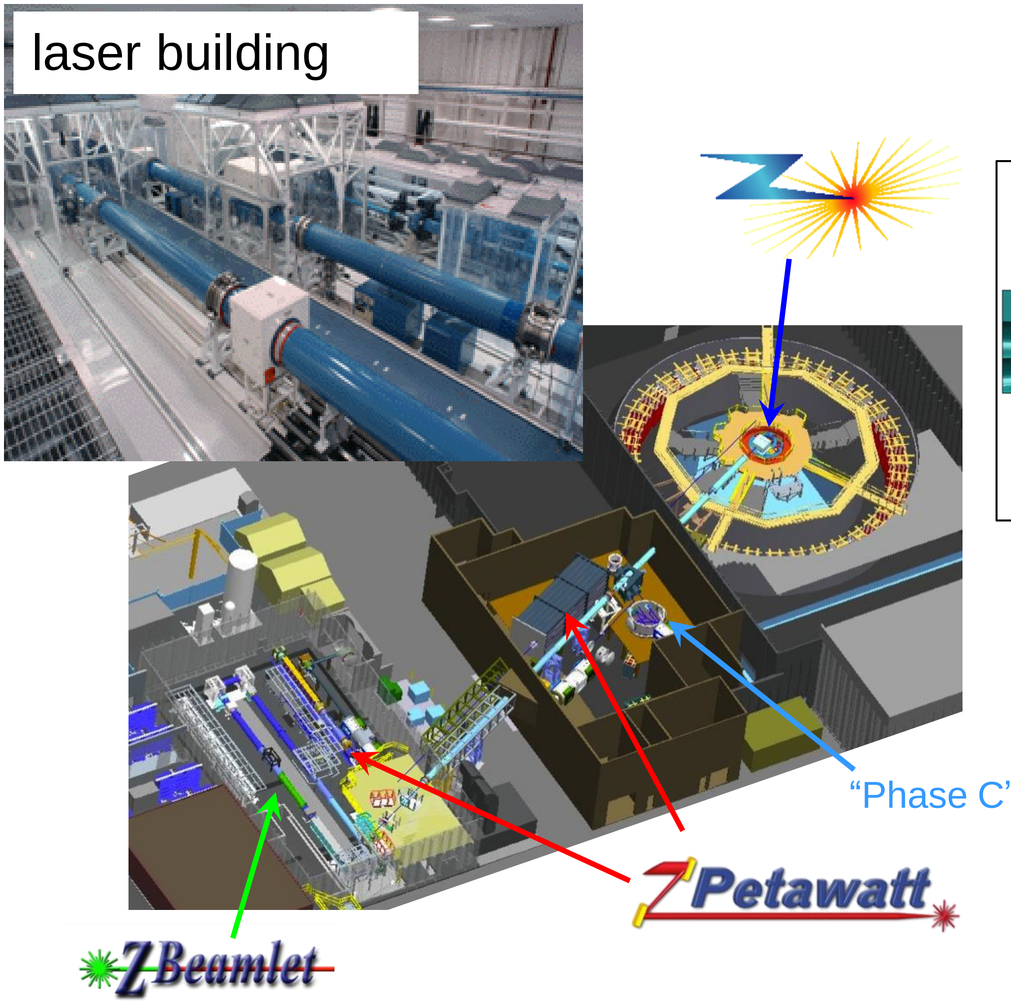
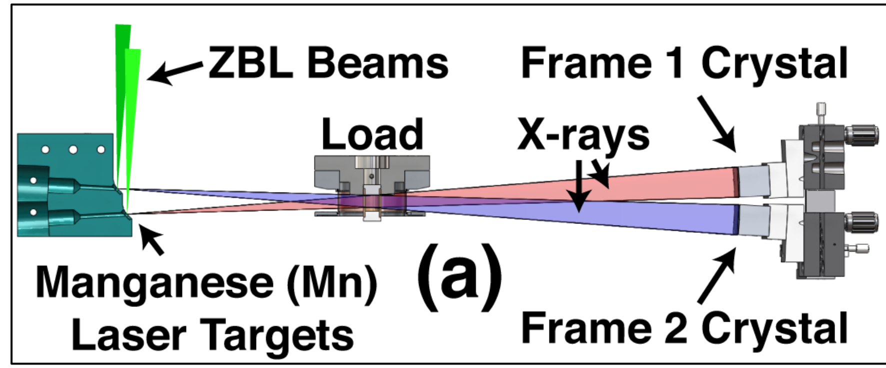


The multi-kJ, 2-TW Z-Beamlet Laser (ZBL) at Sandia* is being used to heat fusion fuel and to radiograph liner target implosions (ICF program primary user of facility)



Today ZBL is routinely used to deliver 1-2.5 kJ of 2ω light in 1-2 pulses for radiography.

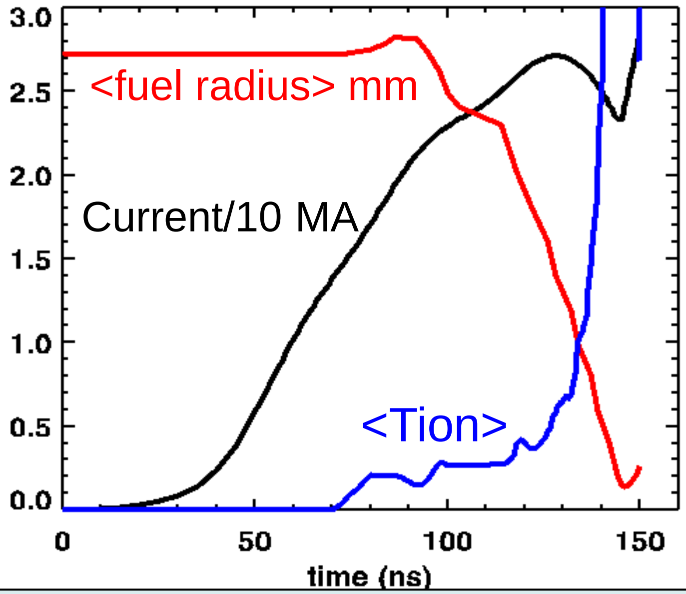


We are upgrading the laser's bandwidth to provide 4 kJ over 4 ns to targets on Z in 2014

Other upgrades are possible that would increase this to 8-10 kJ, increasing our chance of success

* P. K. Rambo *et al.*, Applied Optics 44, 2421 (2005).

Example MagLIF parameters for a 27 MA shot on Z



We are using both LASNEX and HYDRA to do two-dimensional integrated MagLIF simulations

- Well benchmarked
- Radiation hydrodynamics
- Includes the effect of B on alphas

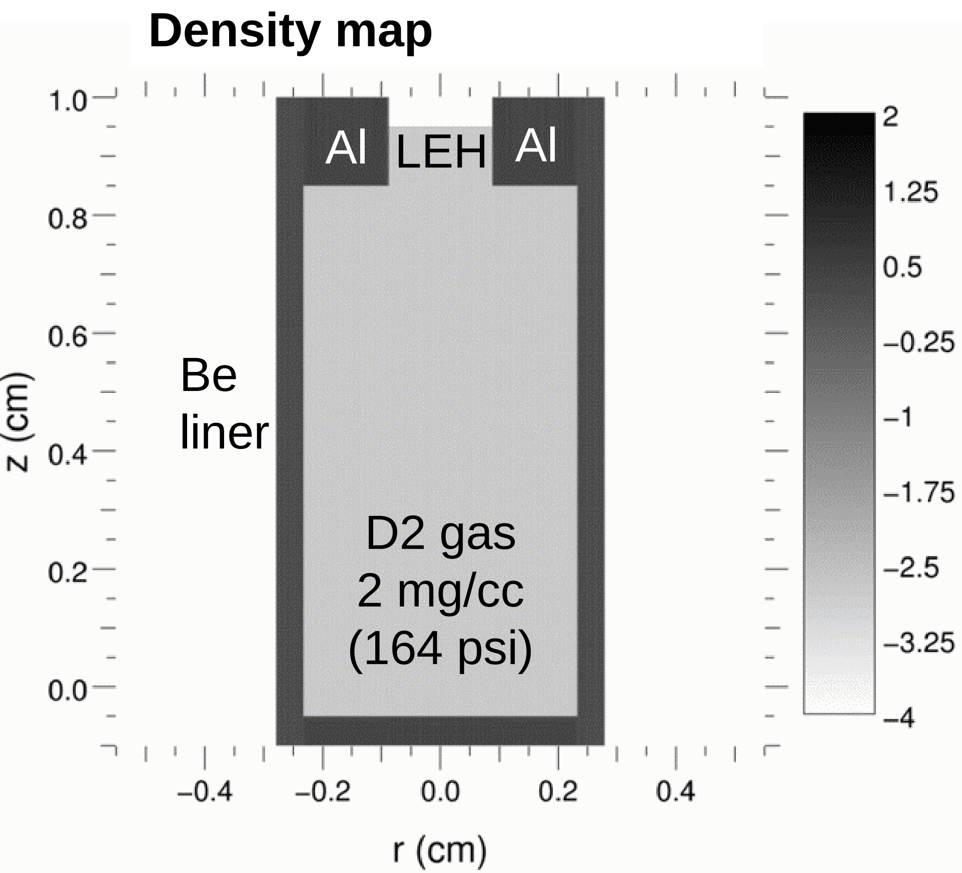
Example MagLIF simulation parameters

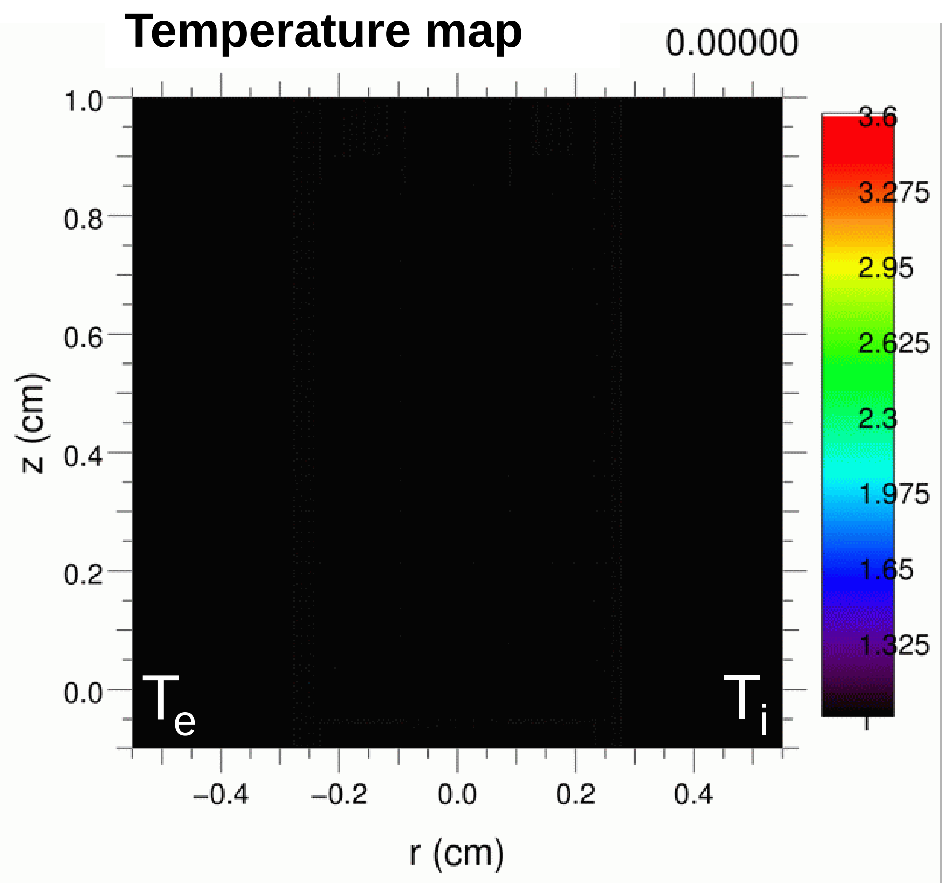
• Beryllium liner R_0	2.7	mm
• Liner length	5.0	mm
• Aspect Ratio $R_0/\Delta R$	6	
• Initial fuel density	0.003	g/cc
• Preheat temperature	250	eV
• Initial B-field	30	Tesla
• Peak current	27	MA
• Convergence Ratio	23	
• Peak Pressure	3	Gbar
• Fuel Energy	120	KJ
• Total absorbed energy	600	KJ
• Final fuel density <on axis>	0.5	g/cc
• Peak central averaged Tion	8	keV
• Final peak B-field	13500	Tesla
•1D Yield	500	kJ

Note: Fuel β varies from ~80 at preheat to ~5 at stagnation—main effect of Bfield is suppression of thermal conduction losses

*S.A. Slutz *et al.*, Phys. Plasmas 17, 056303 (2010).

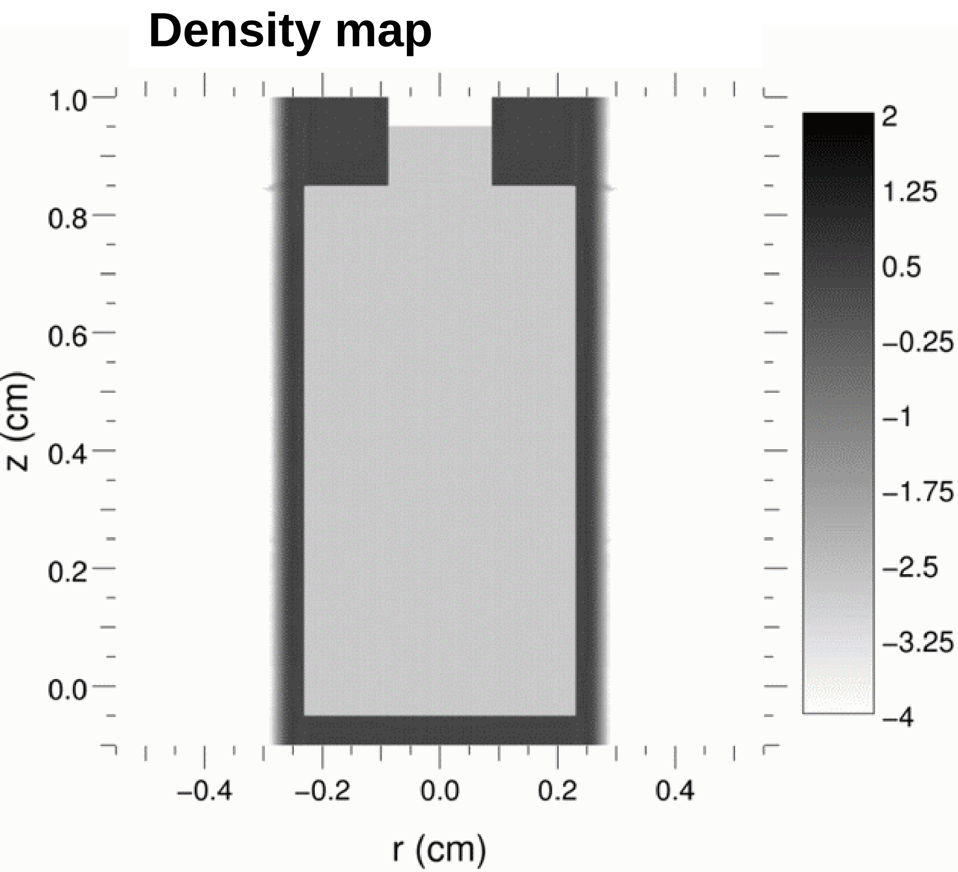
An example fully integrated 2D HYDRA calculation illustrates the stages of a MagLIF implosion

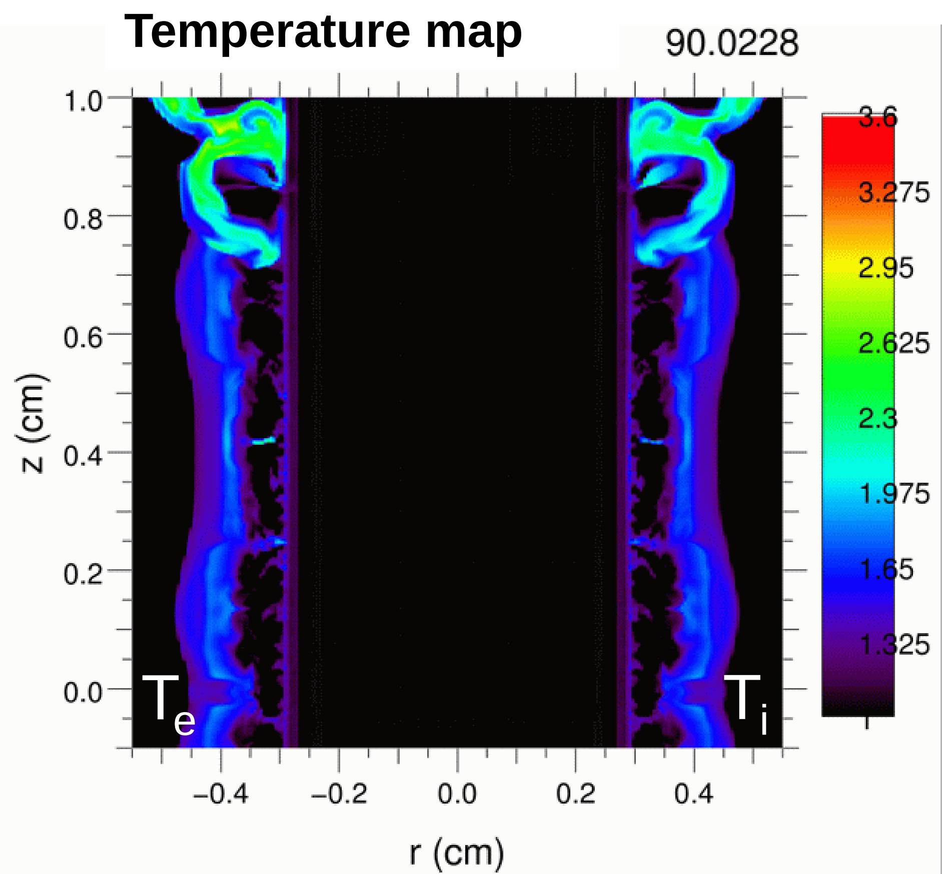




Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

The fusion fuel is preheated using the Z-Beamlet laser after the liner begins to implode





Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

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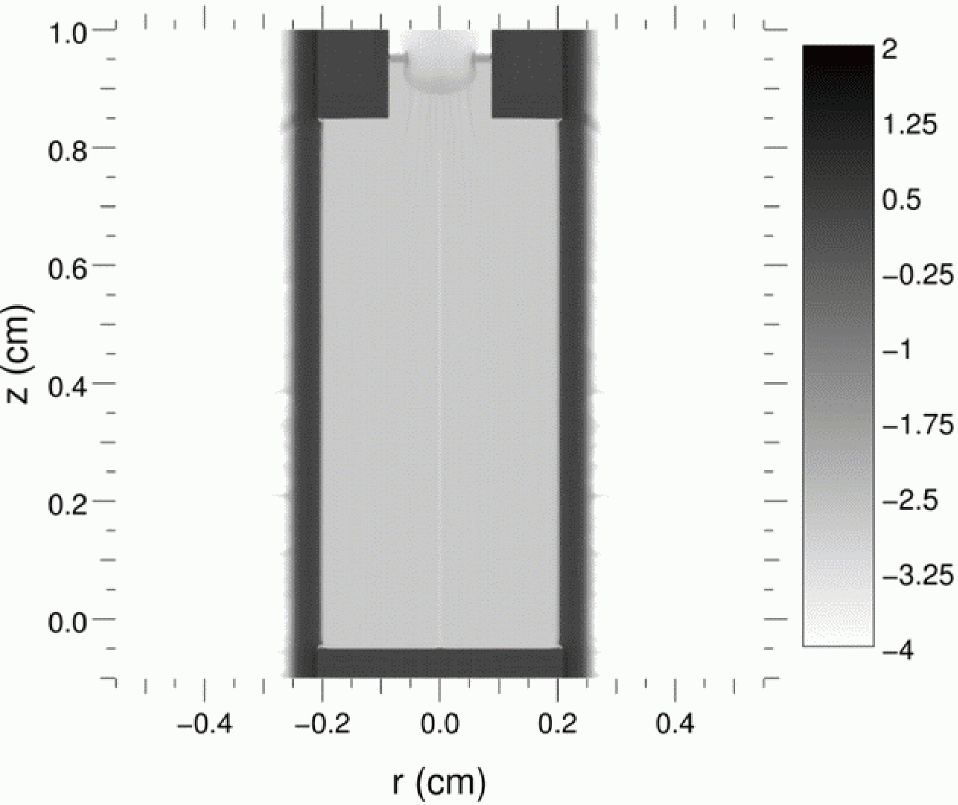
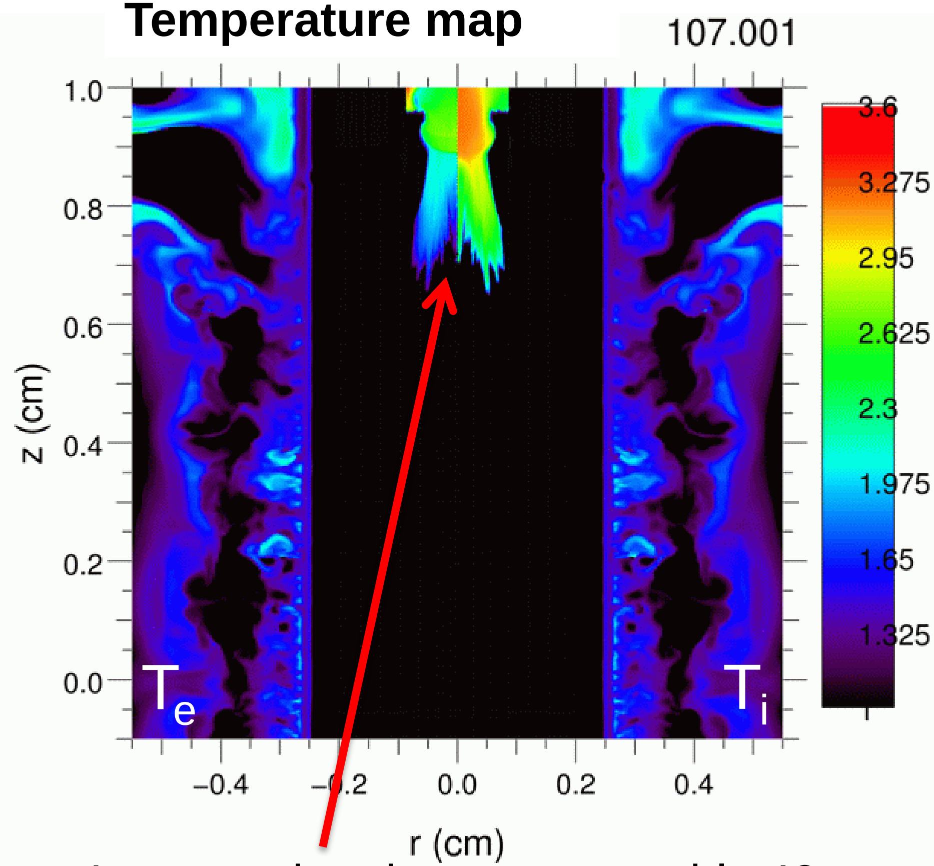
Density map



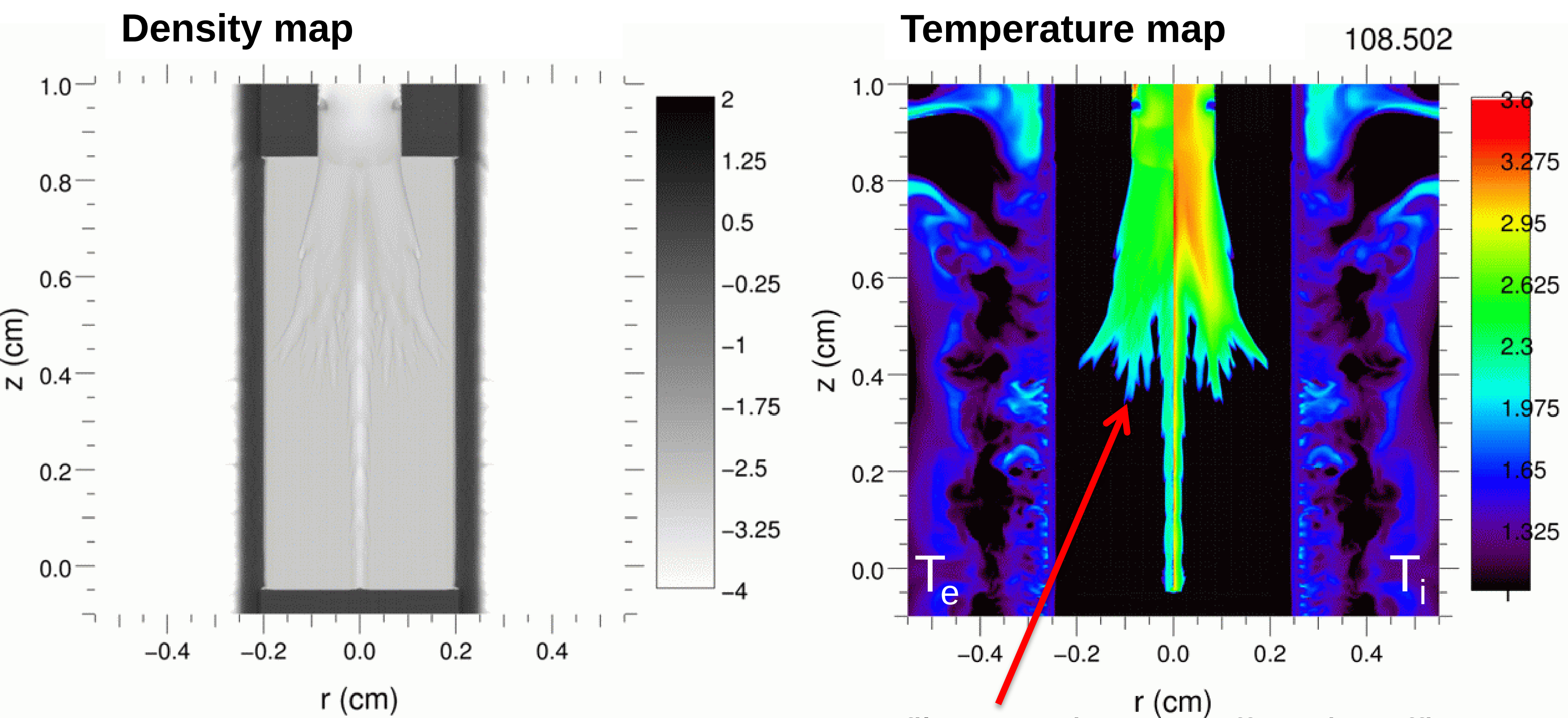
Temperature map



Laser preheating starts roughly 40 ns before the liner reaches the axis

Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

The fusion fuel is preheated using the Z-Beamlet laser after the liner begins to implode

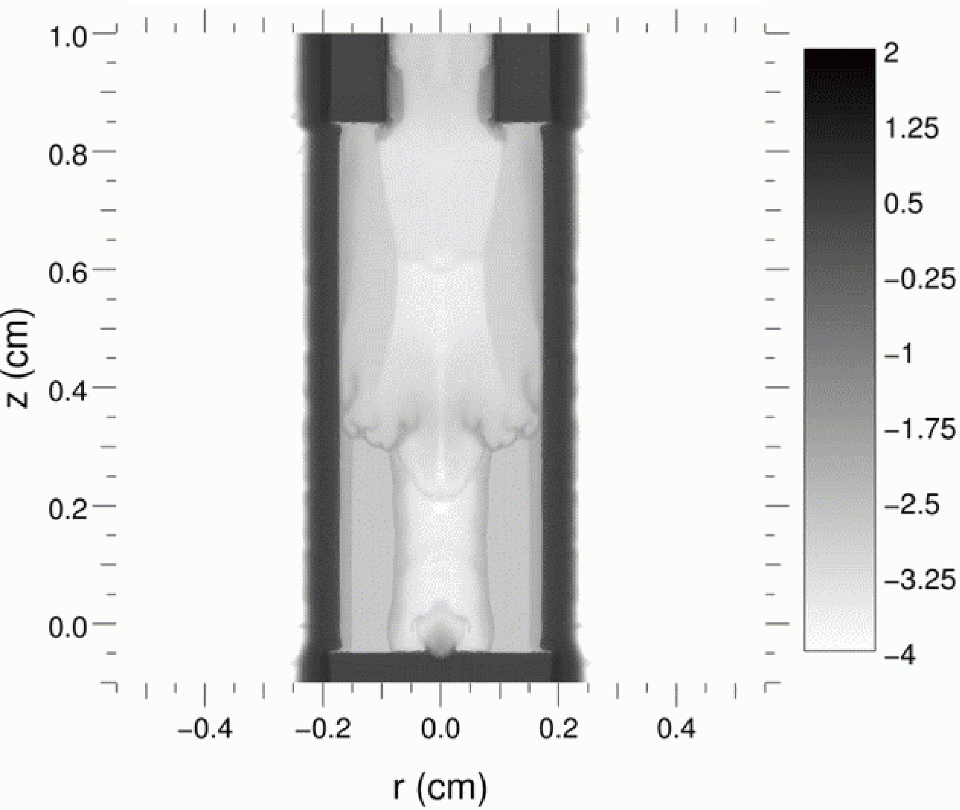


Beam filamentation can affect the efficacy and depth of laser coupling to the fuel

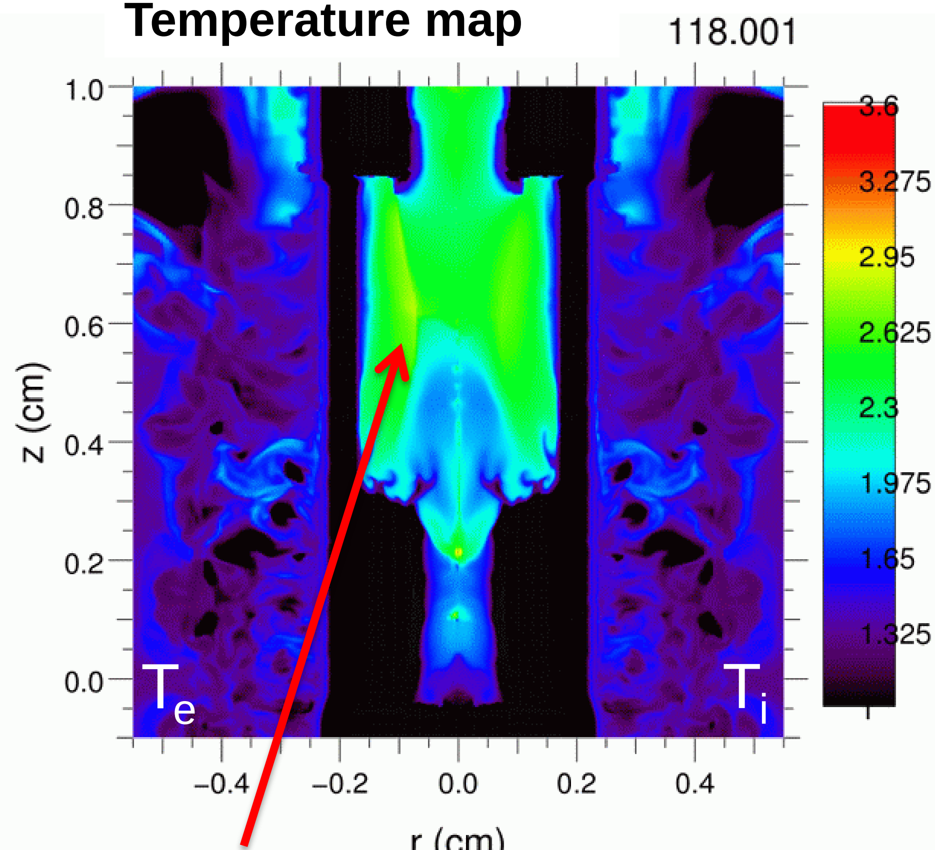
Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

The preheated fuel is then compressed by the imploding liner, reducing the convergence required to reach fusion temperatures

Density map



Temperature map



Initially high peak temperatures (~1 keV) relax to ~300 eV as the energy diffuses into the fuel

Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

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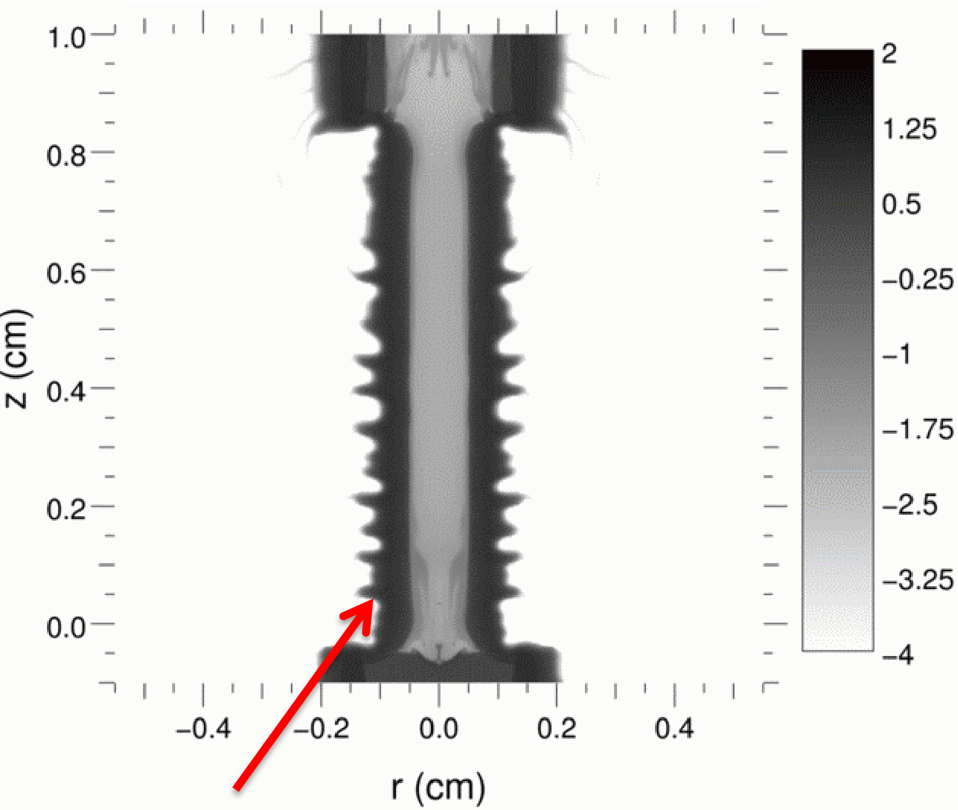
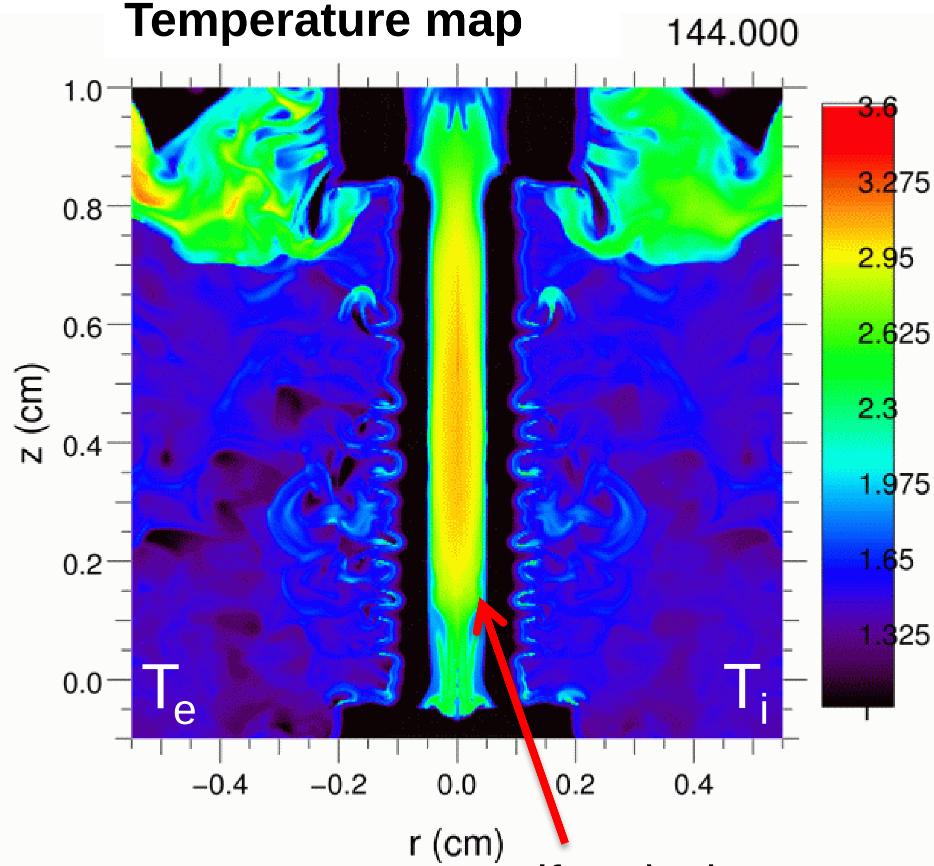
Density map



Temperature map

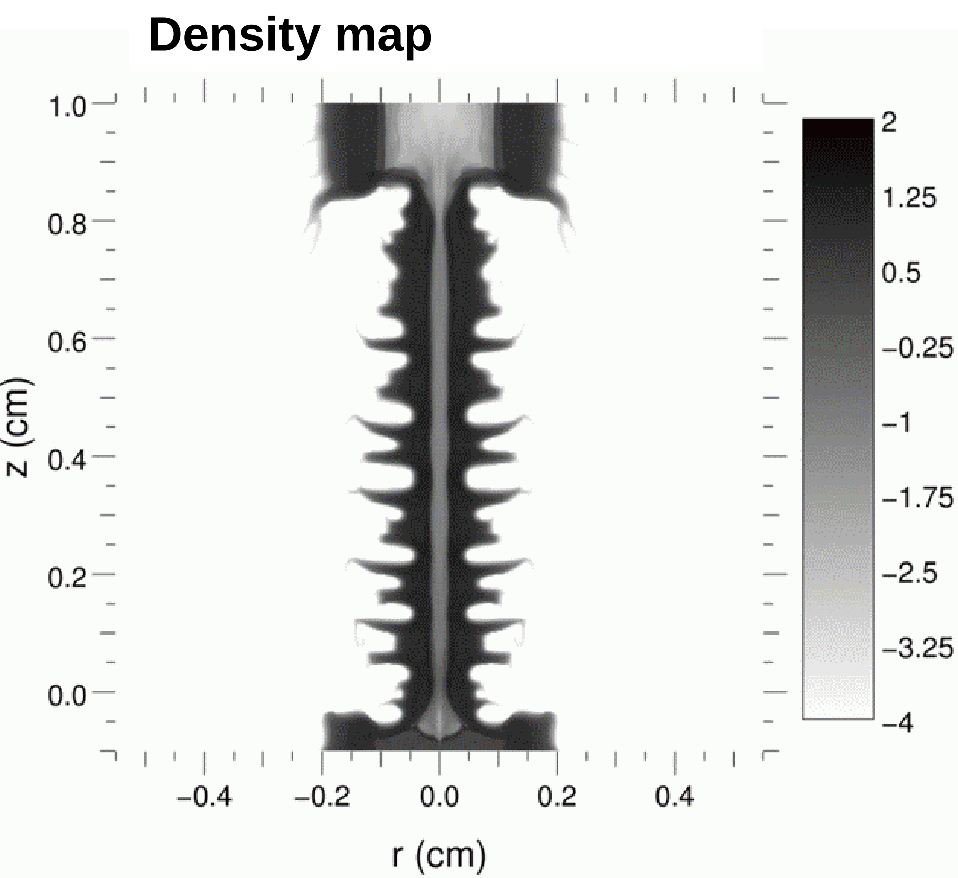


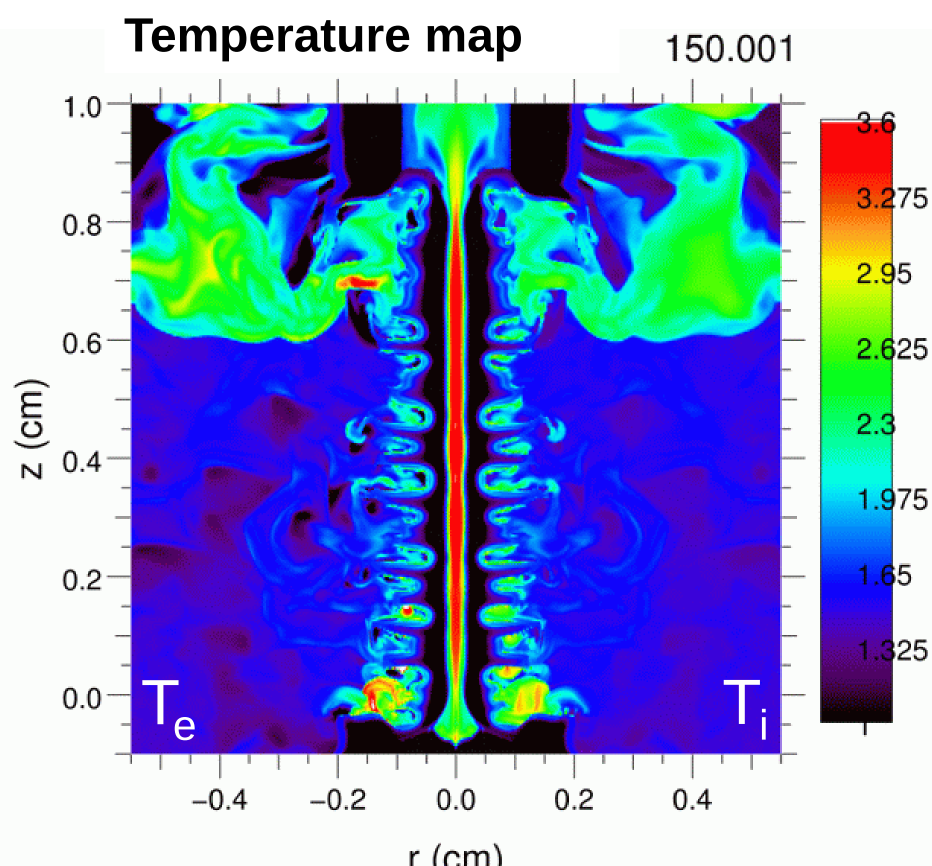
Instabilities develop on the outside liner surface, but impact on fuel mitigated by use of thick liner

Temperature non-uniformity is smoothed out during compression

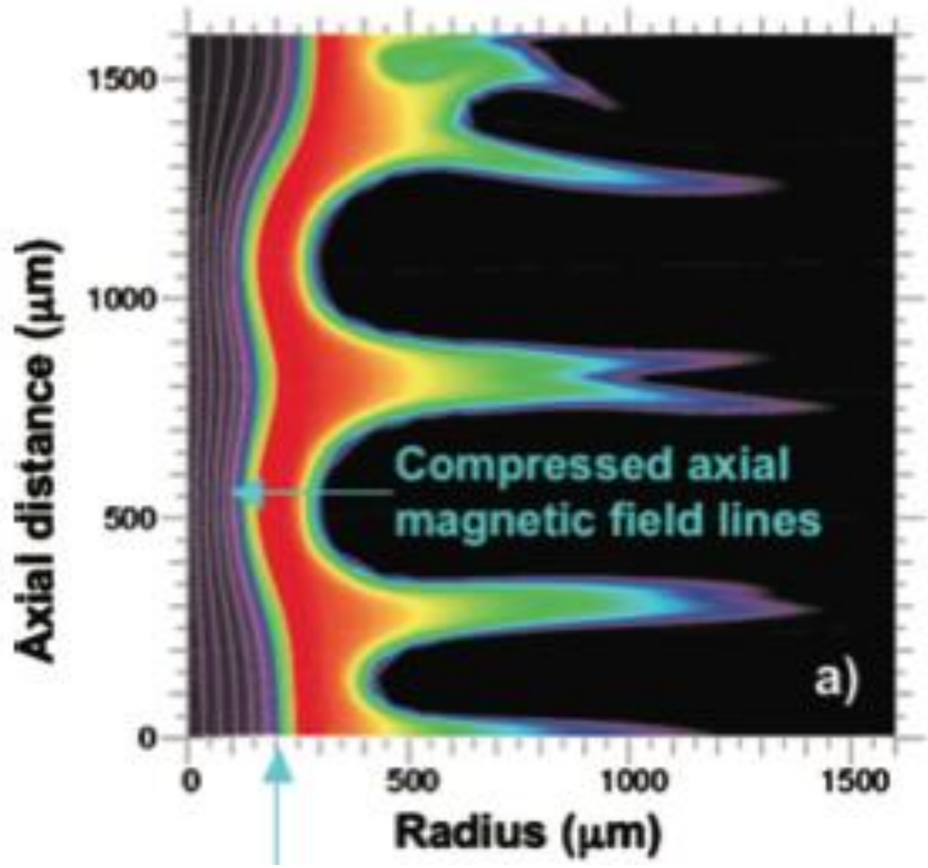
Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

The preheated fuel is then compressed by the imploding liner, reducing the convergence required to reach fusion temperatures



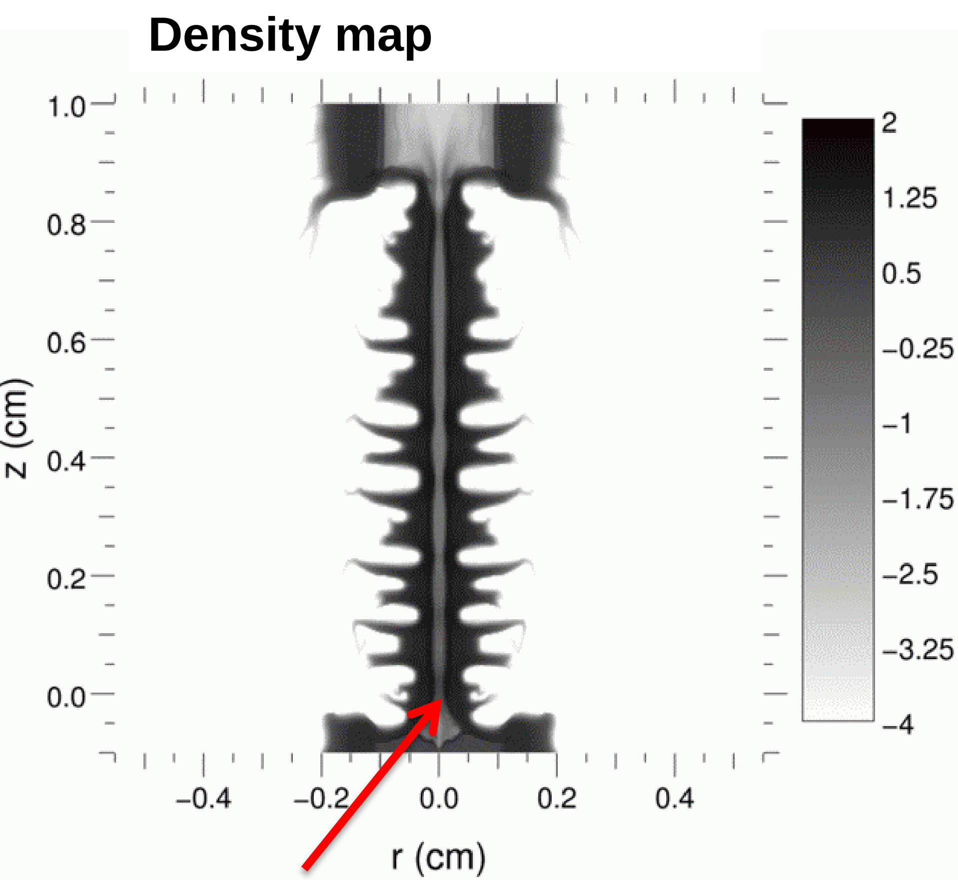


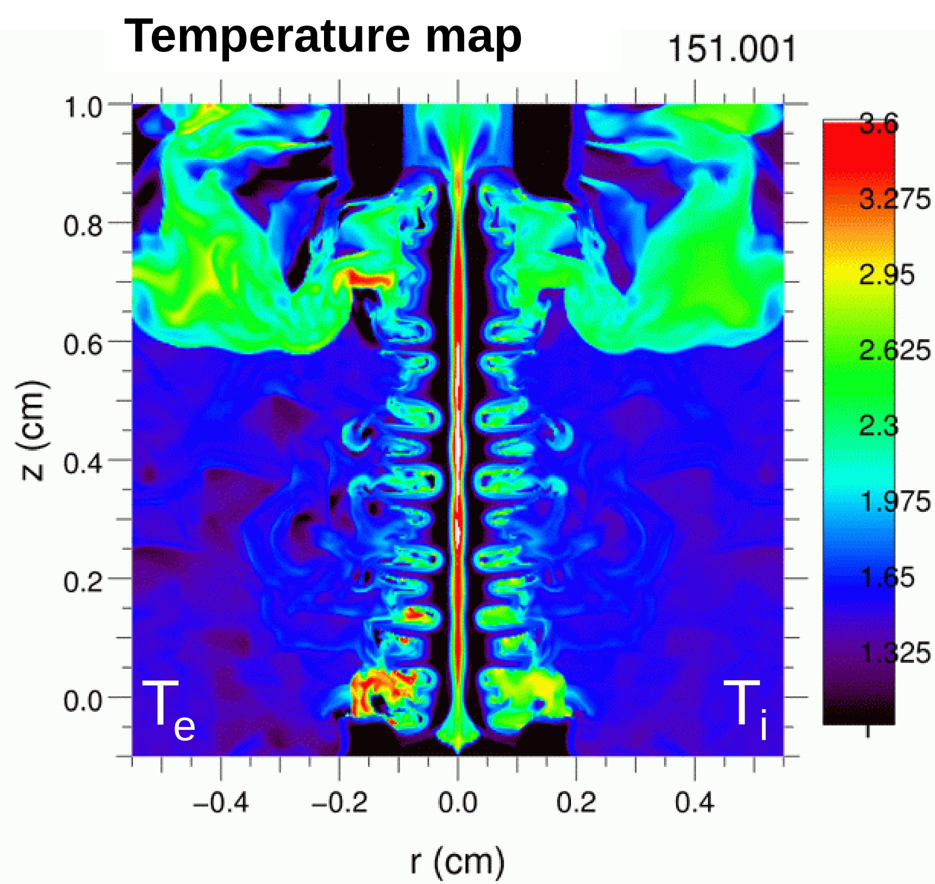
The axial magnetic field is compressed by the liner (some loss due to Nernst) and suppresses heat loss to the relatively cold liner



The axial magnetic field is compressed by the liner (some loss due to Nernst) and suppresses heat loss to the relatively cold liner

The preheated fuel is then compressed by the imploding liner, reducing the convergence required to reach fusion temperatures



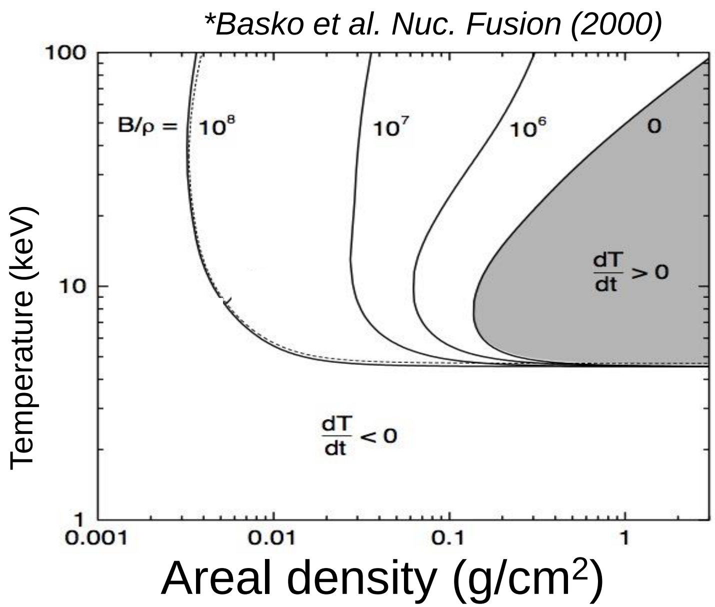


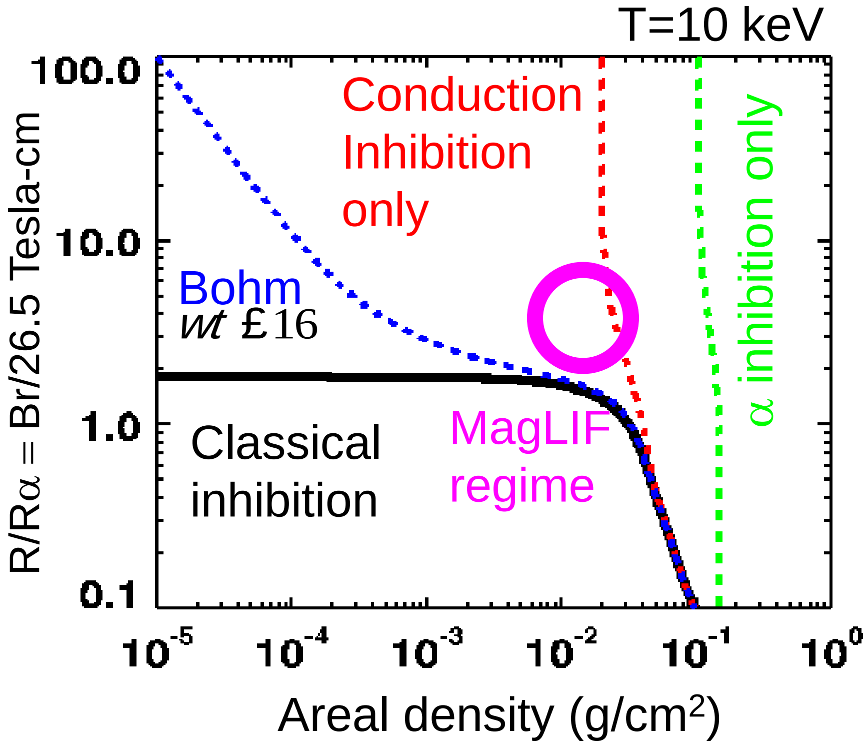
Final fuel density ~1 g/cc
Inertial confinement provided by liner

Final temperature ~8 keV
Peak Bfield >10000 T, Radial CR~23

Example calculations by A.B. Sefkow: DD fuel, I=18 MA, B_Z=10 T, E_{LASER}=2.6 kJ

Fuel magnetization increases the ignition space (regime where cold fuel can be heated for high gain); the required minimum fuel ρr is replaced with a minimum Br





Axial α-trapping requires closed field lines or moderately high fuel density so that $\rho\Delta z > 0.5 g/cm^2$

MagLIF experiments can test some of the key physics underlying many fusion concepts relying on fuel magnetization to relax requirements

We have been building up the capability for several years to do fully-integrated Z experiments in 2013, we believe a goal of 100 kJ-equivalent yields in 2015 is feasible

- Initial experimental parameters
  - Load current: 16-20 MA --demonstrated Dec. 2012
  - Applied B-field strength: 10 Tesla --demonstrated on Z Feb. 2013
  - Laser preheat energy: 1-2 kJ --demonstrated on Z July-Sept. 2013
  - Fuel: DD
- Experimental parameters expected in 2015
  - Load current: >24 MA (largely through facility upgrades)
  - Applied B field: 30 Tesla
  - Laser preheat: 4-10 kJ (>4 kJ requires further laser upgrades)
  - Fuel: DD
- We are considering building up to trace tritium levels by 2016, similar to staged approach adopted by U. Rochester

We installed an 8 mF, 15 kV, 900 kJ capacitor bank in 2013 to drive 10-30 T axial fields over a several cm^3 volume for MagLIF, successfully used on several Z experiments at >20 MA, 10 Tesla

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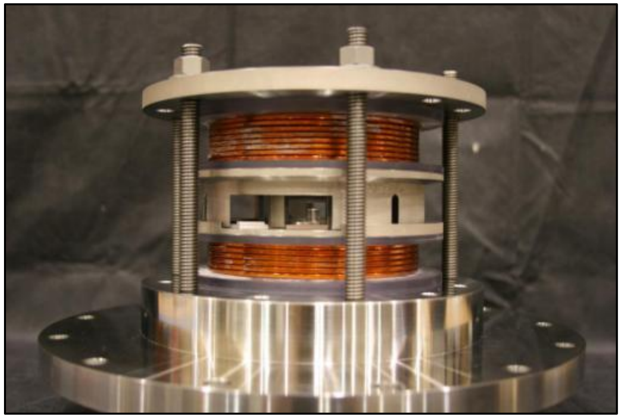
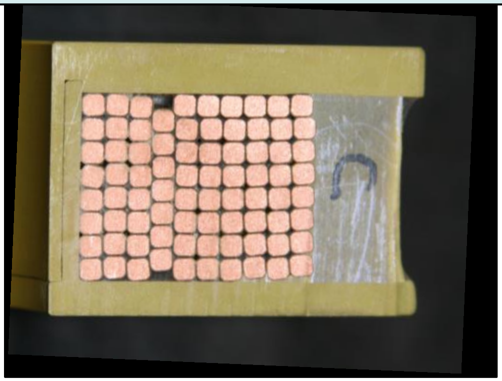
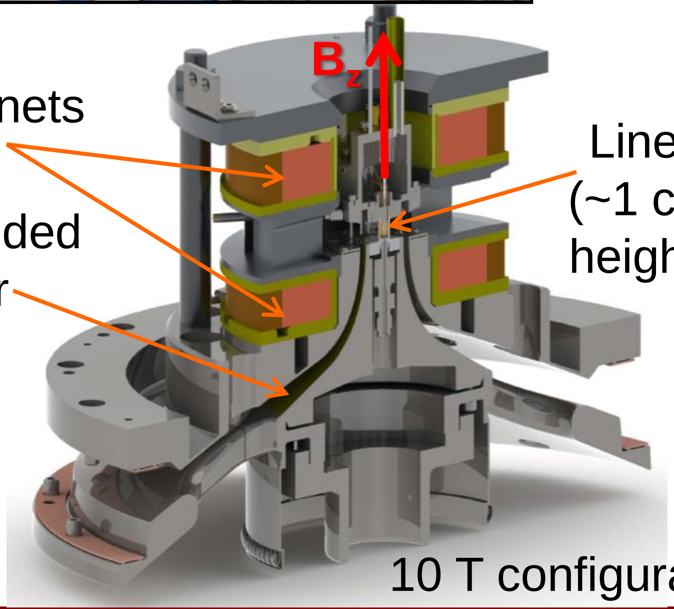
Capacitor bank system on Z 900 kJ, 8 mF, 15 kV (Feb. 2013)

Example MagLIF coil assembly with copper windings visible

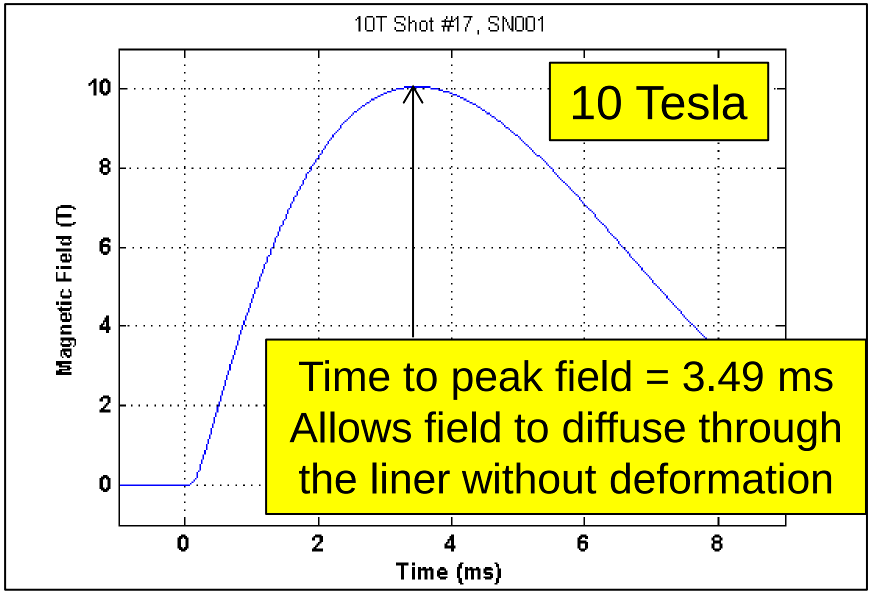


Cross section of coil showing Cu wire, Torlon housing, and Zylon/epoxy reinforcement





10 T configuration

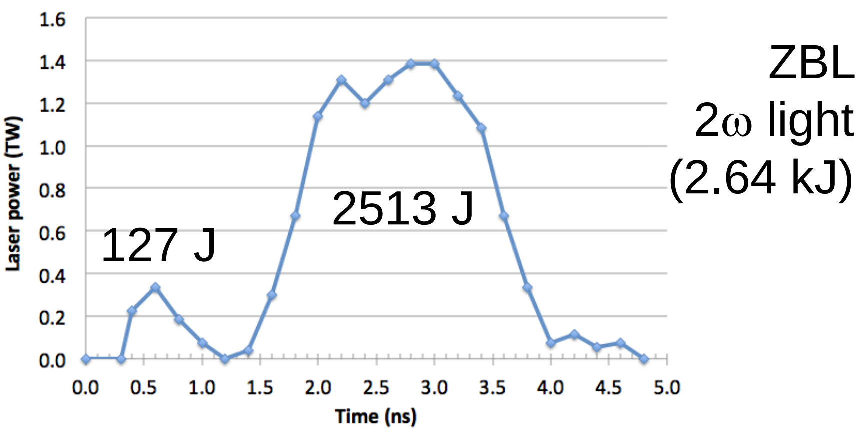


Time to peak field = 3.49 ms
Allows field to diffuse through the liner without deformation

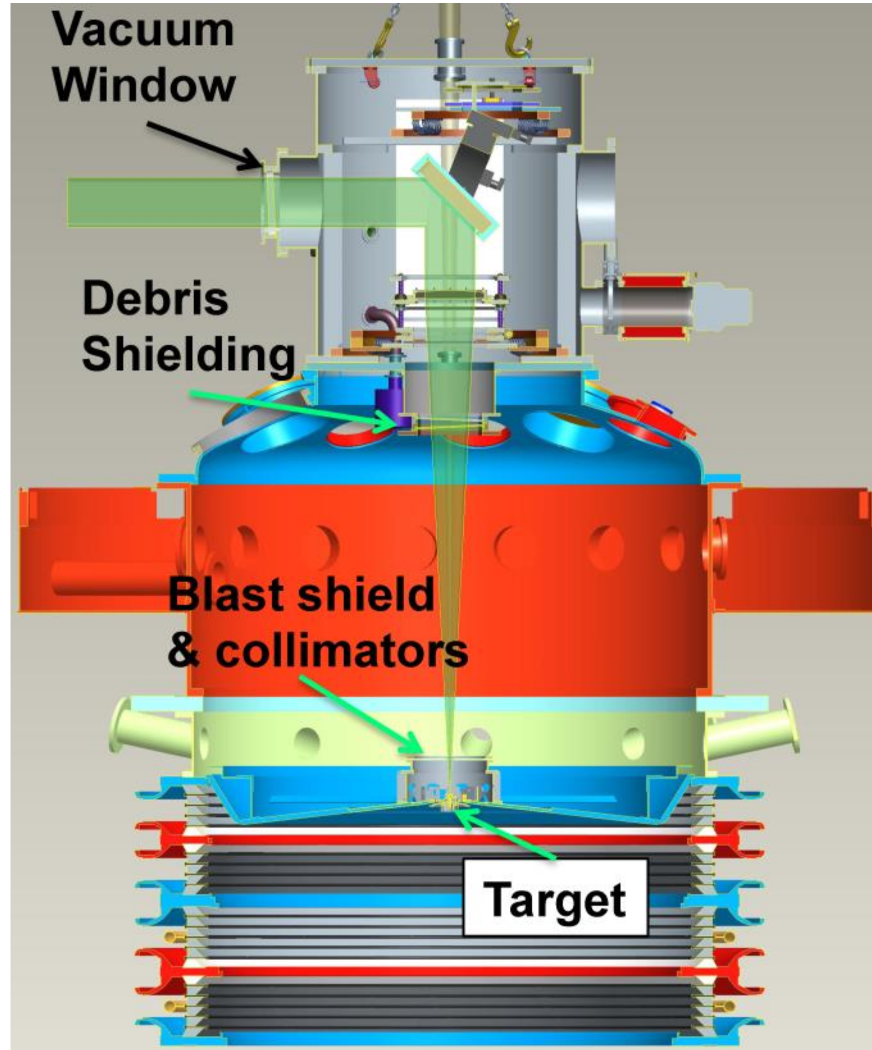
Coil technology and capacitor bank capable of up to 30 T fields over same volume

Commissioning of a new vacuum final optics assembly to allow 2 kJ preheating on a Z experiment is ongoing

Example pulse measurement



Prepulse vaporizes gas-containing foil; main pulse couples to DD fuel



We are pursuing several campaigns of science-focused experiments using Z, Z-Beamlet, and Omega-EP

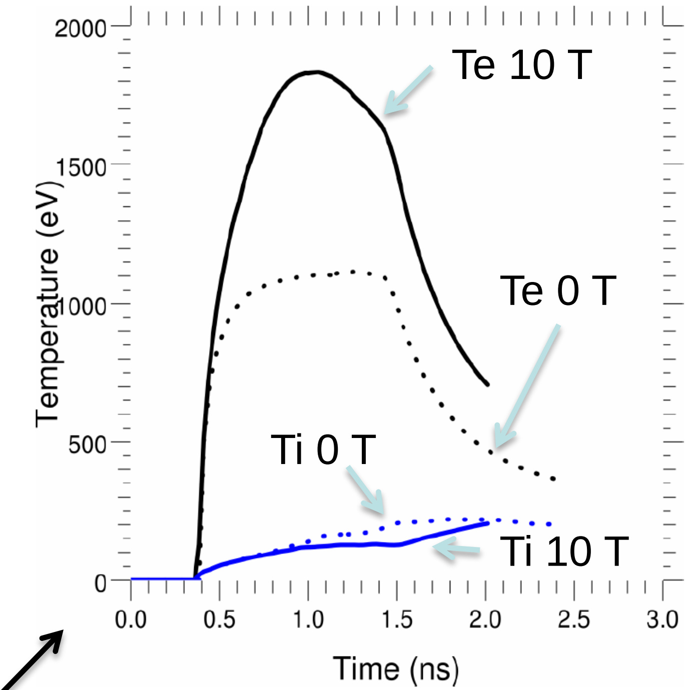
- Liner Stability (2008-2015)
  - Demonstrate we can reach necessary convergence with good stability
  - Magneto-Rayleigh-Taylor instability (acceleration & deceleration)
  - Electro-thermal instability (seeds MRT instability)
- Magnetic Flux Compression (2013-2015)
  - Demonstrate we are compressing the magnetic field with liner
- Fuel Preheating (2013-2015)
  - Demonstrate we are heating the fusion fuel as predicted, concern about beam filamentation and other laser-plasma interaction issues
  - Tests using Z-Beamlet limited by lack of a strong diagnostic suite
- Suppression of heat loss using magnetic fields (2014-2015)
  - Demonstrate that magnetic fields suppress electron conduction as expected under our unique temperature & density conditions
  - Can do this work on Omega-EP using MIFEDS capability, taking advantage of their extensive diagnostic suite

We are designing experiments for Omega-EP to begin understand the physics of magnetized & preheated plasma, awarded 2 days on Omega-EP in FY2014 to start this

- Previous work used a laser (1ω, 100 J, 1 ns) to heat a magnetized N jet (ne = 1.5e19/cc) with a 12 T peak B field (Froula, PRL 2007)
- They found electron thermal conduction was suppressed according to classic Braginskii models for heat transport

- We propose to extend this to plasma densities 20x higher, plasma temperatures 5x hotter, using 50x greater laser energy available at Omega-EP

- Effect of 10 T B field on laser-heated plasma dynamics/temperature of laser heated plasma expected to be large/observable
- Near-Braginskii transport under these conditions would be good news for MagLIF!



Ion and electron temperature profiles from HYDRA with and without a 10 T applied B field for a 2mg/cc D2 gas heated with a 3ω laser delivering 2.5 kJ in 1 ns

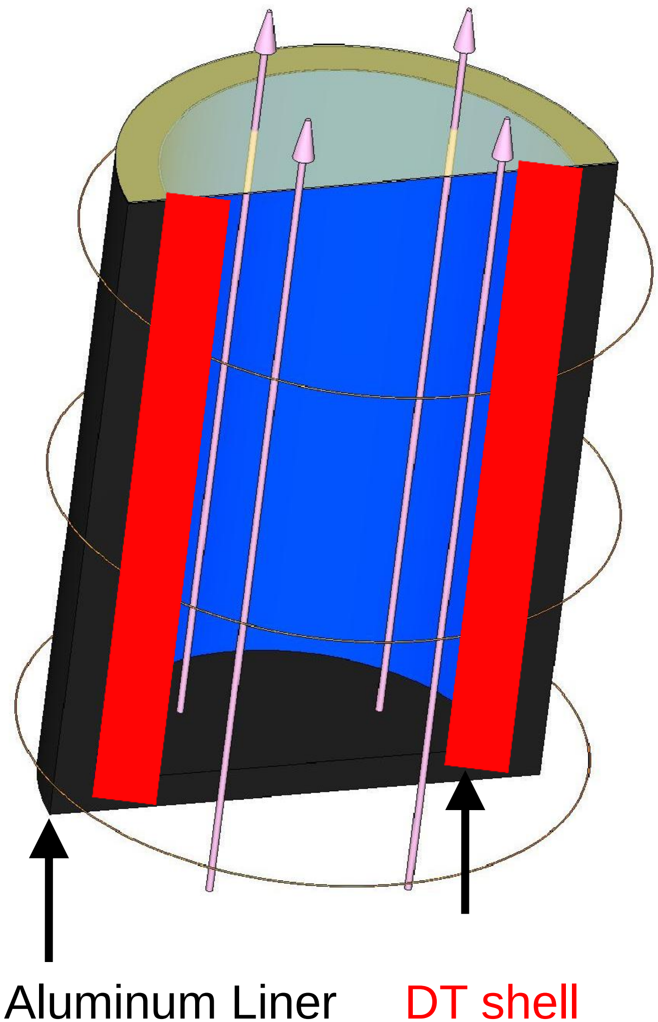
Understanding heat suppression is fundamental and data are scarce--more could be done

We have begun fully-integrated tests of MagLIF idea this year at reduced parameters. A breakeven-equivalent experiment by 2015 (using DD fuel) is feasible

- We have a plan for science-focused experiments to identify, measure, predict, and ideally demonstrate control over key physical phenomena
  - Requires a significant number of experiments both on Z and on laser facilities (e.g., Omega-EP, Z-Beamlet)
  - Some issues require new diagnostics, target fabrication, and/or simulation capabilities (e.g., advanced MHD in HYDRA)
- We have built an initial capability for integrated MagLIF tests on Z
  - We are leveraging significant target, hardware, and diagnostic infrastructure previously developed to support other experiments on Z (ICF is only 25% of the total program on Z facility)
  - The last key capability, a new final optics assembly to enable on-axis laser preheating, is currently being implemented (e.g., testing this week)
- We have a path forward to do integrated assessments of MagLIF at relevant scales in 2015 (using DD fuel)
  - Initial capabilities deployed in 2013 are not optimal (10 T, 2 kJ, 20 MA)
  - We are planning to improve these for 2015 (30 T, 4-10 kJ, >25 MA)
  - Improved capabilities will allow a credible assessment

Other slides for help during discussions

A levitated shell version of MagLIF could give high yield and high gain on a larger facility*



INITIAL CONDITIONS

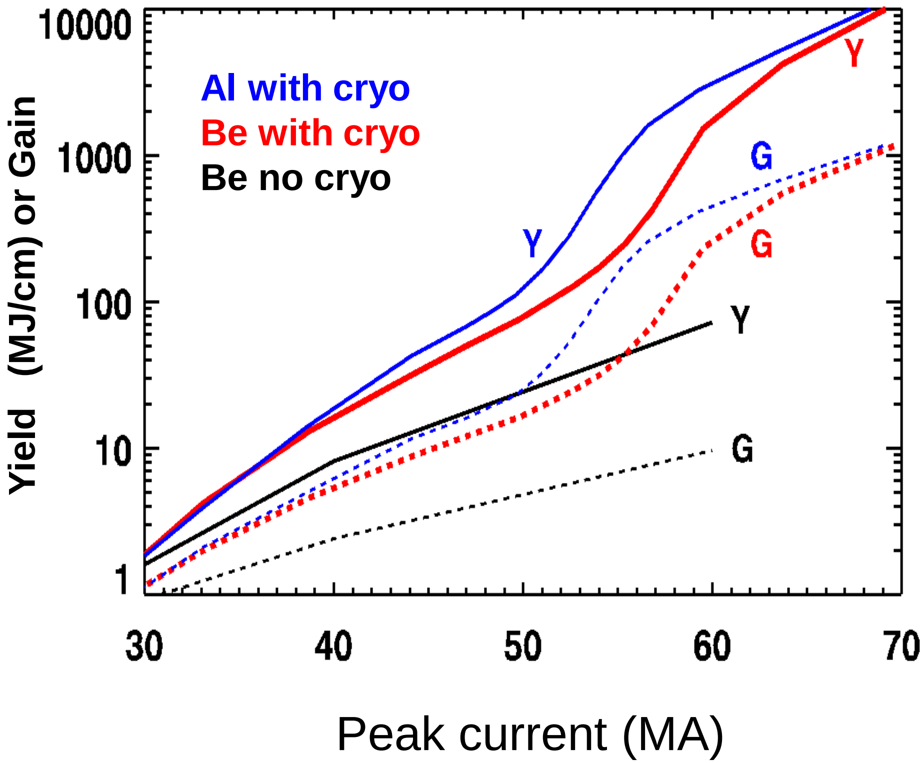
Peak Current:	61 MA
Al Liner R0:	4.4 mm
Liner height:	10 mm
Aspect ratio (R0/ΔR):	6
Initial gas fuel density:	10 mg/cc
Initial B-field:	10 T

FINAL CONDITIONS

Target Yield:	4.8 GJ
Target Gain:	700
Convergence ratio (R0/Rf):	22
Final on-axis fuel density:	9.3 g/cc
Final peak B-field:	12500 T

* S.A. Slutz and R.A. Vesey, Phys. Rev. Lett. (2012).

One-dimensional scaling studies* suggest Gains >1000 are possible with MagLIF at currents >50 MA



Further optimization is possible

- **Fuel is not on a low isentrope**
- **No current pulse shaping**

Margin increases with current >50% as I => 70 MA

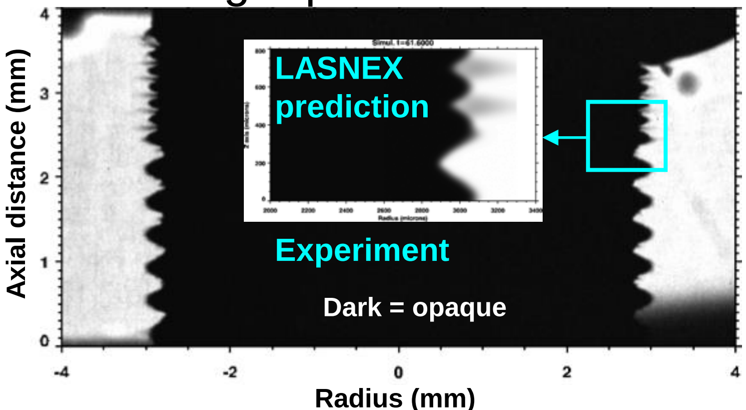
Initial gas density increases with current

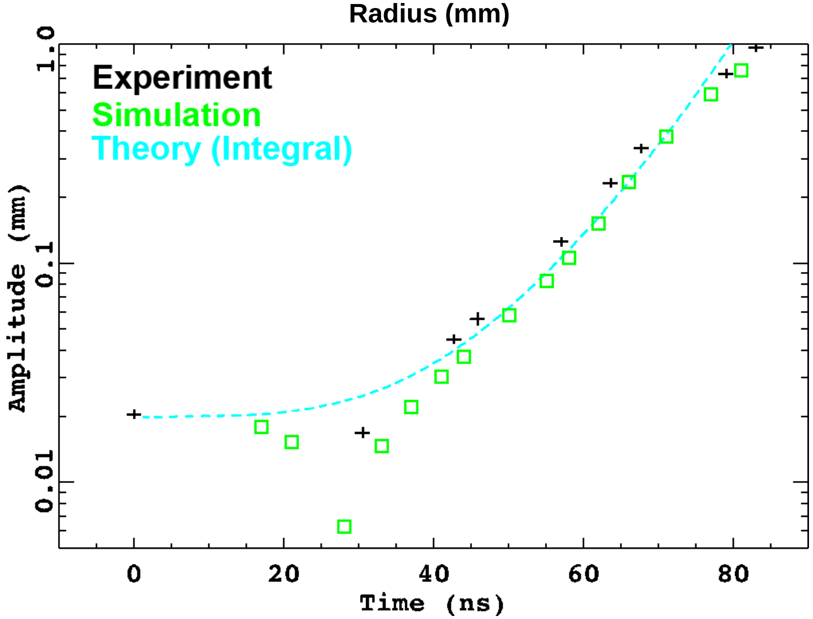
- **not at vapor pressure**
- **laser energy =>22 kJ**
- **pulse length => 30 ns**

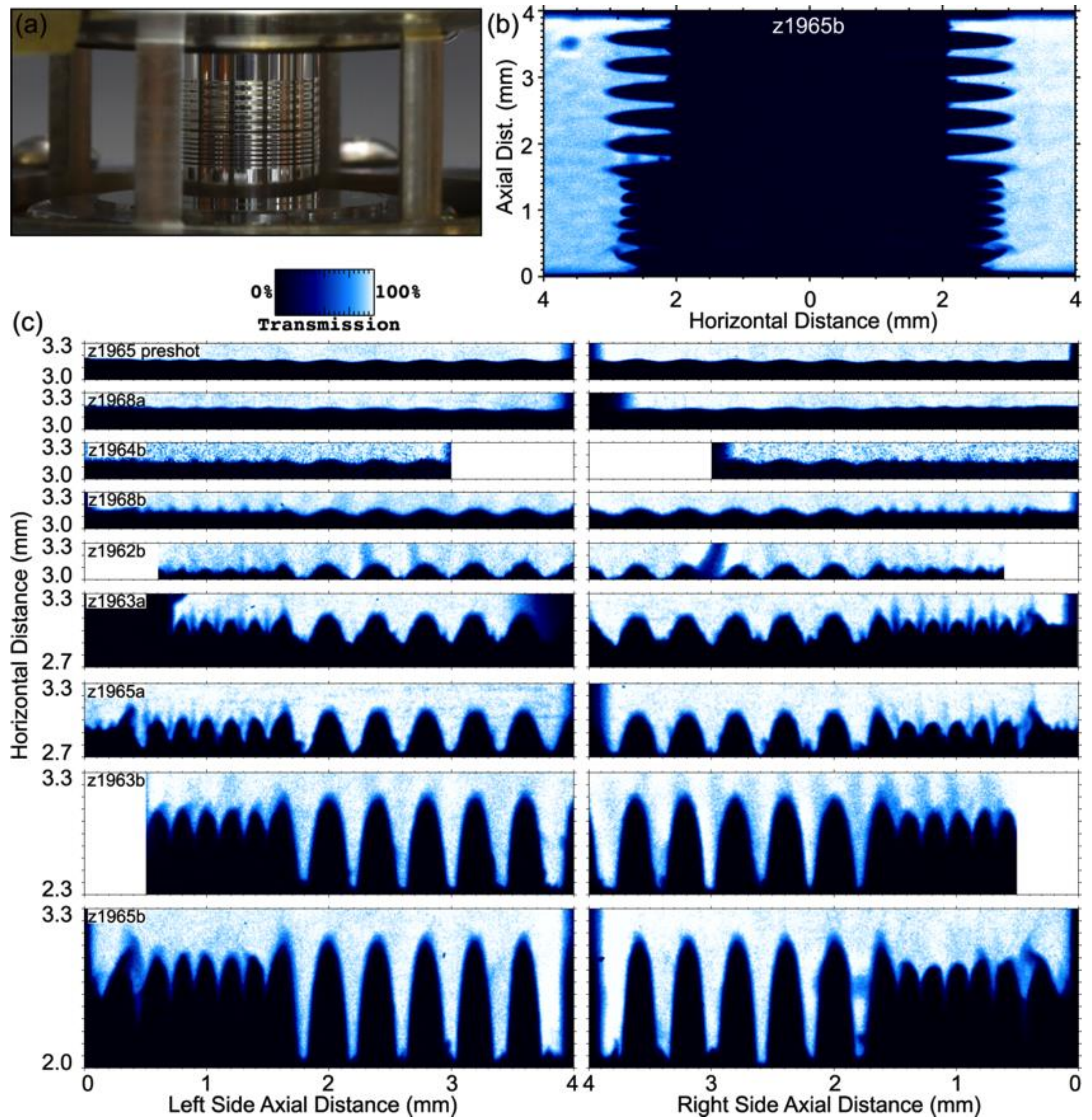
* S.A. Slutz and R.A. Vesey, Phys. Rev. Lett. (2012).

We did controlled experiments as the first critical test of our understanding of the Magneto-Rayleigh Taylor instability

Radiographs captured growth of intentionally-seeded 200, 400-μm wavelength perturbations

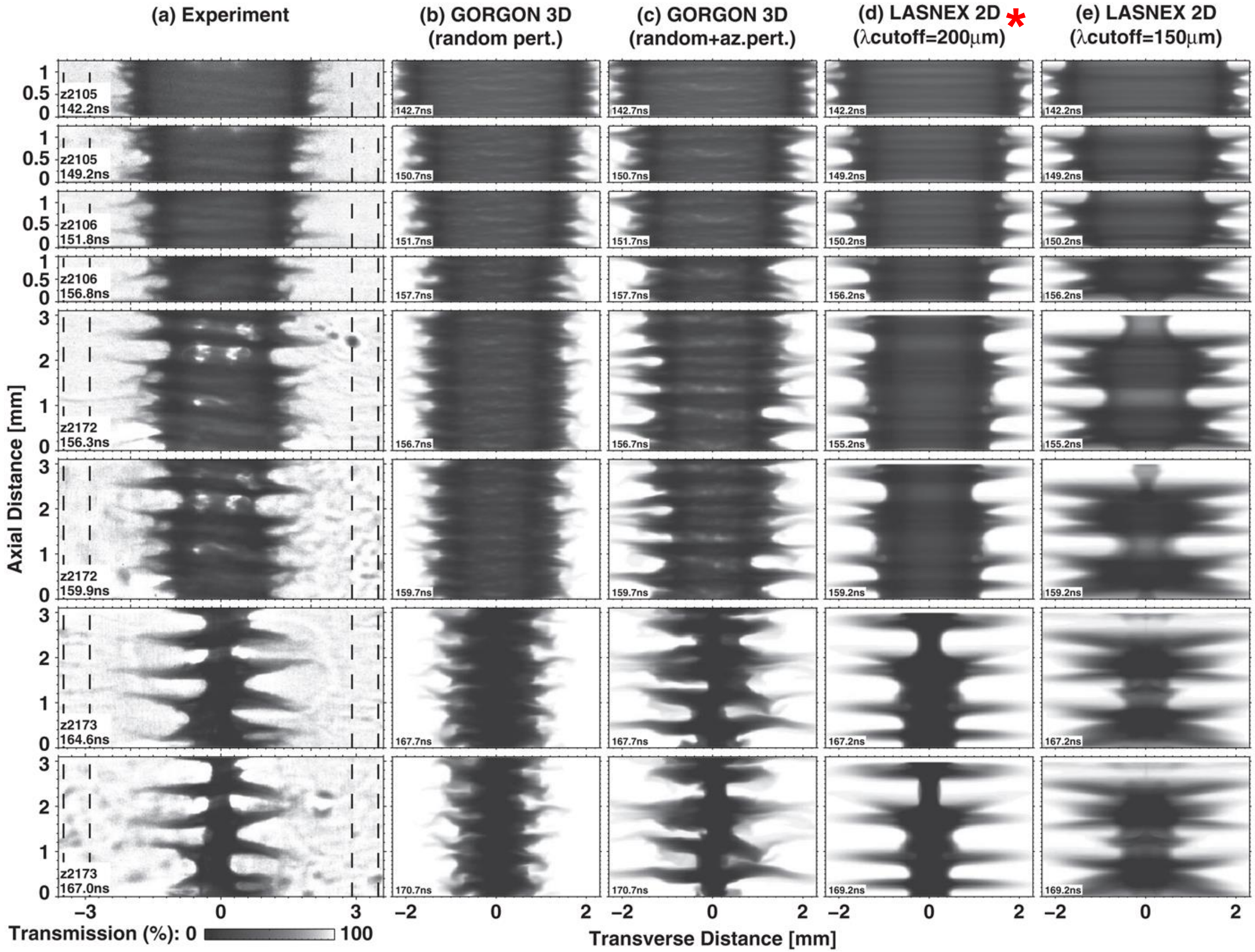






D.B. Sinars *et al.*, Phys. Rev. Lett. (2010); D.B. Sinars *et al.*, Phys. Plasmas (2011).

Beryllium experiments show surprisingly correlated instability growth at late times that may imply a highly-correlated initial perturbation



R.D. McBride *et al.*, Phys. Rev. Lett. (2012); R.D. McBride *et al.*, Phys. Plasmas 20, 056309 (2013).

Radiographs of axially-magnetized liner implosions show a dramatic impact of the field

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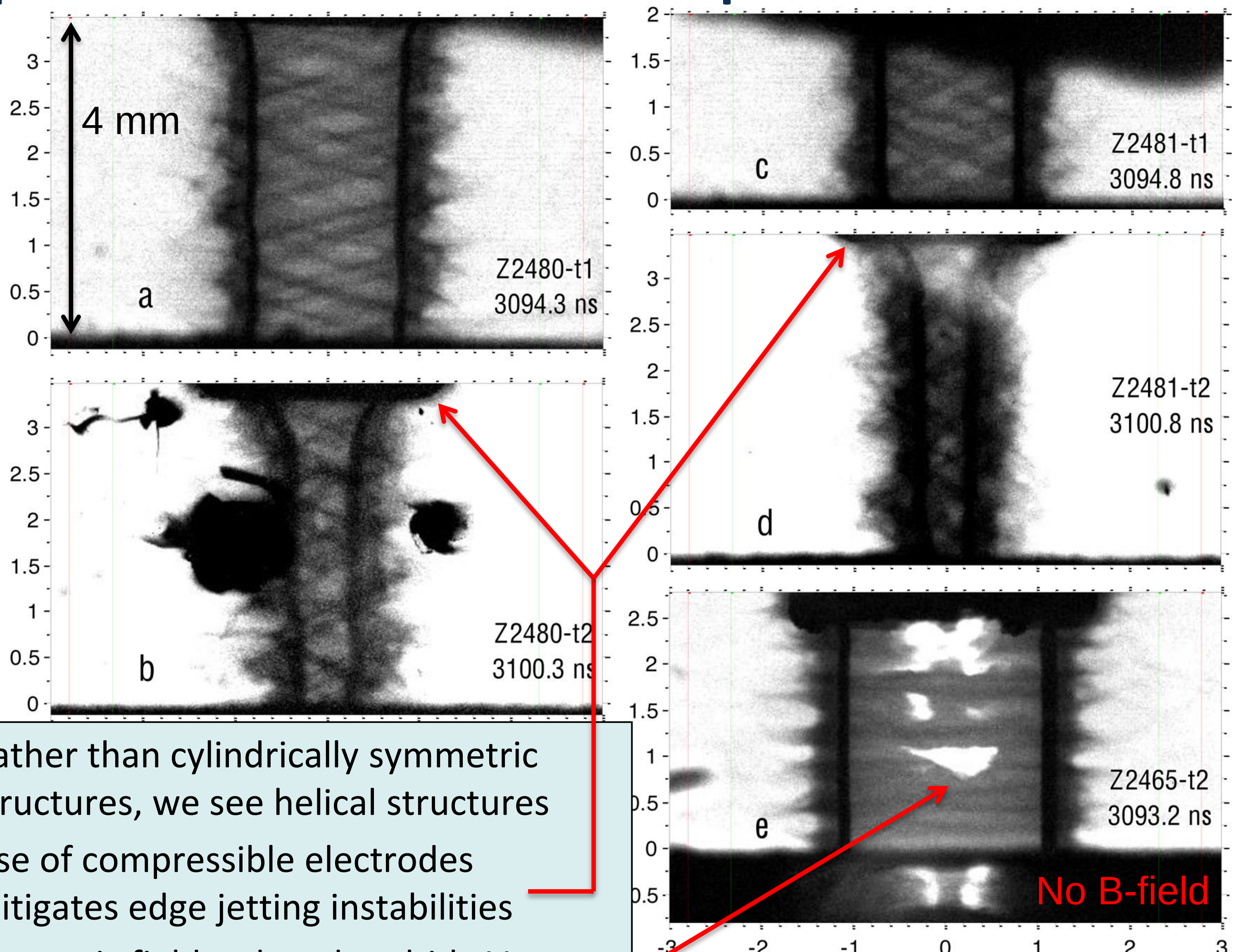


CR =2.7

CR =6.4

CR =2.9

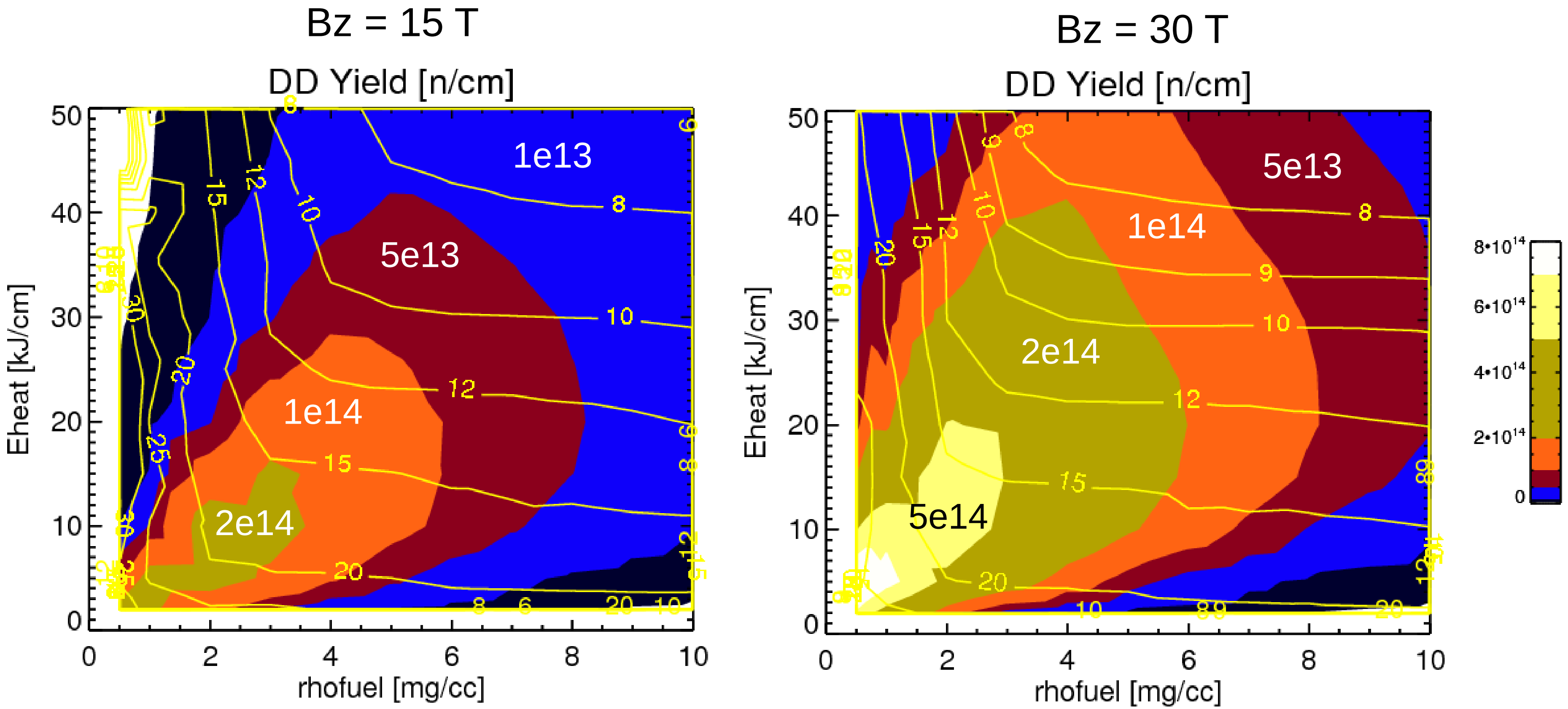
CR =6.9

Highest CR imaged to date

CR =2.0

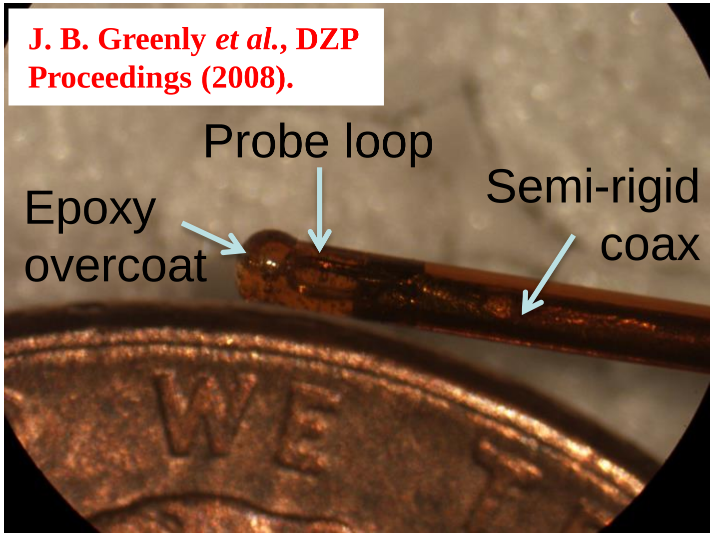
- Rather than cylindrically symmetric structures, we see helical structures
- Use of compressible electrodes mitigates edge jetting instabilities
- Magnetic field reduced multi-keV x rays associated with late-time instabilities

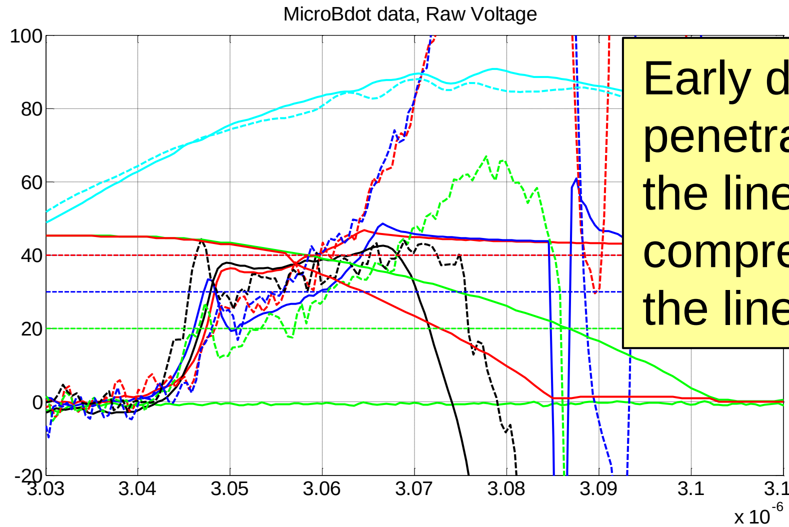
If we could couple more preheat energy to the target, interesting neutron yields can be achieved with the current Z configuration at significantly lower convergence ratios



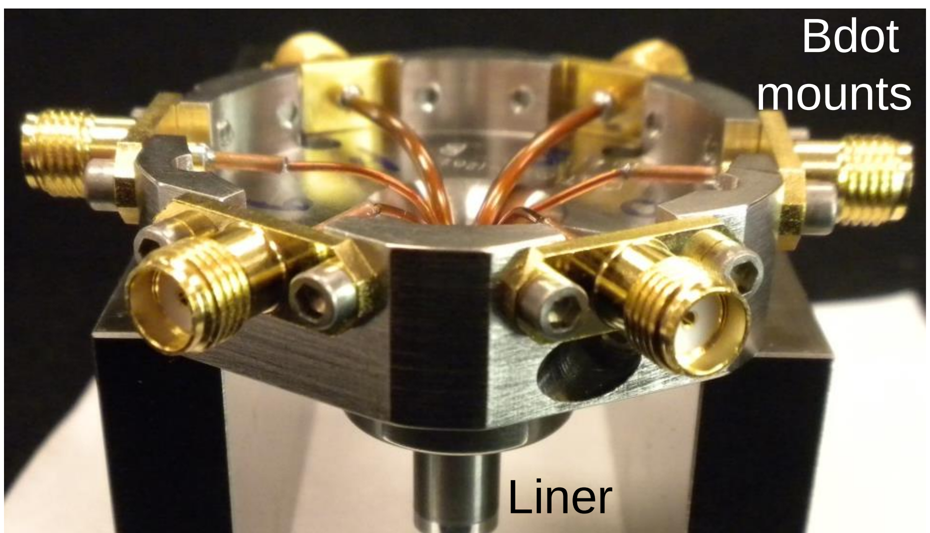
1D contour plots that show how yield (white numbers) and convergence ratio (yellow) vary if significantly more energy (50 kJ) can be coupled to the fuel. Scan done using standard Be MagLIF target, 80 kV marx charge. Values are taken at peak burn.

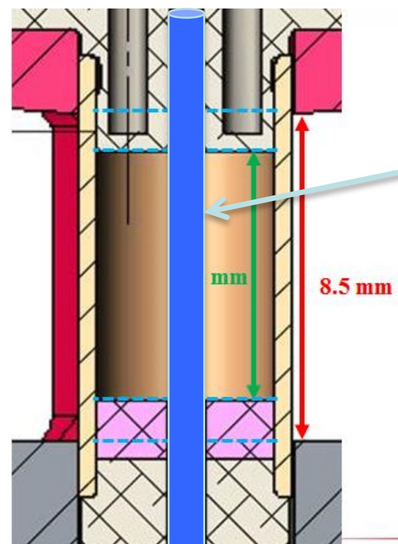
Micro-Bdots developed in collaboration with Cornell are being used to measure magnetic flux compression, we are working with LANL to implement optical Faraday rotation





Early data confirm B_Θ penetration through the liner, and B_z flux compression within the liner



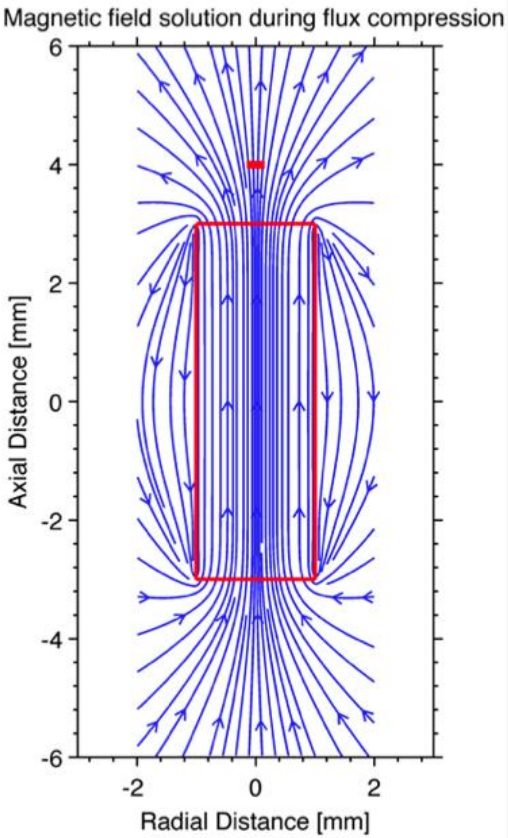


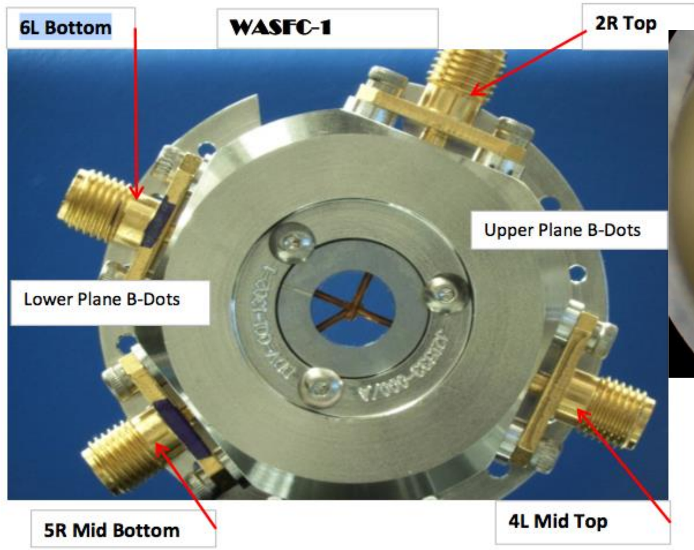
Working with Tom Intrator (LANL) to develop on-axis fiber-based optical Faraday rotation diagnostic (1st attempt Dec. 2013)

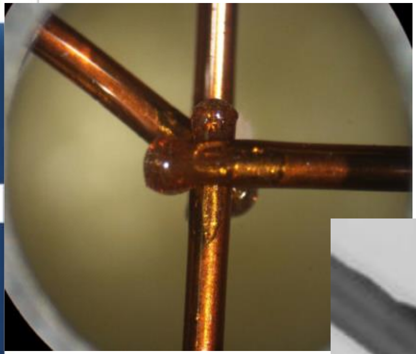
Magnetic flux compression is key to magnetized targets—much more work possible here

We have made our first measurements of flux compression with Bdot probes above the liner

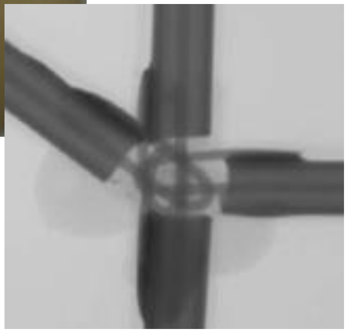
Probes measure the dipole fringing field above the liner



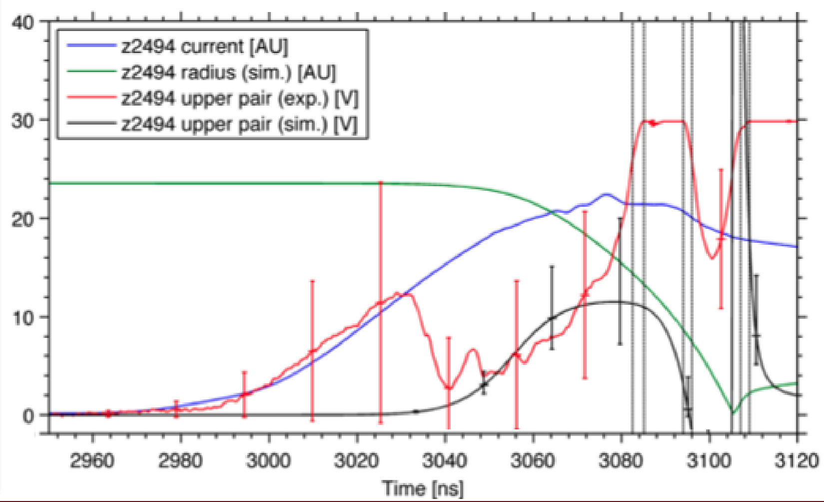




Zoomed Optical Photo



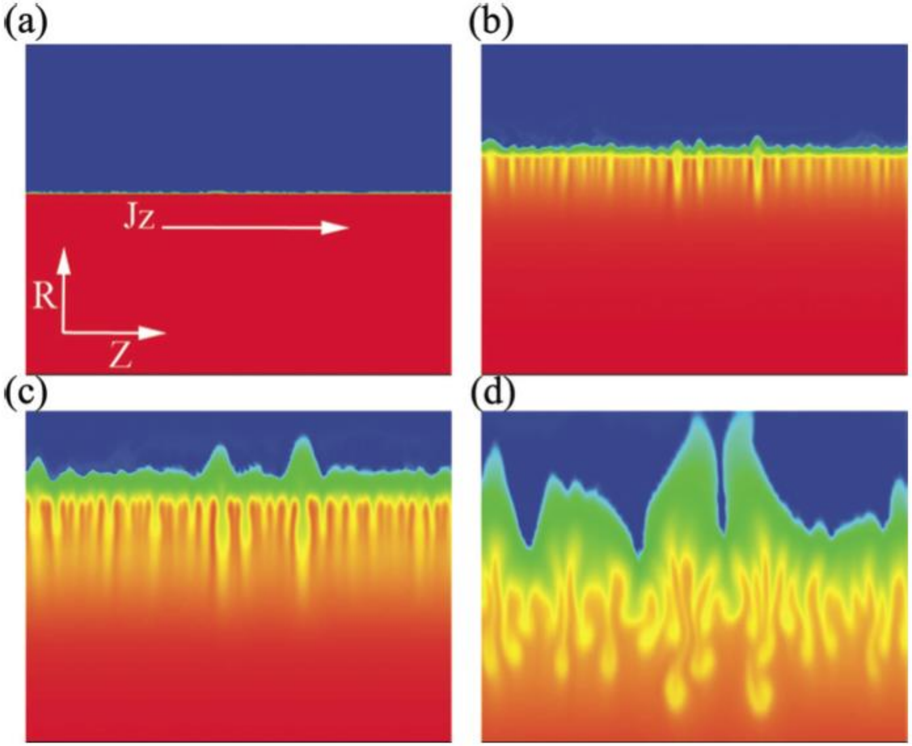
Zoomed X-ray Image of Bdot loops



We are improving the data quality, but our first measurements did show evidence of flux compression during the implosion

Bdot probes developed in collaboration with J. Greenly (Cornell U.)

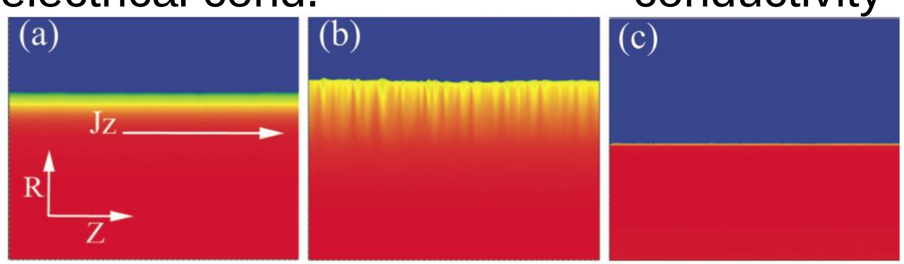
The electro-thermal instability is an important mechanism that could seed MRT growth*

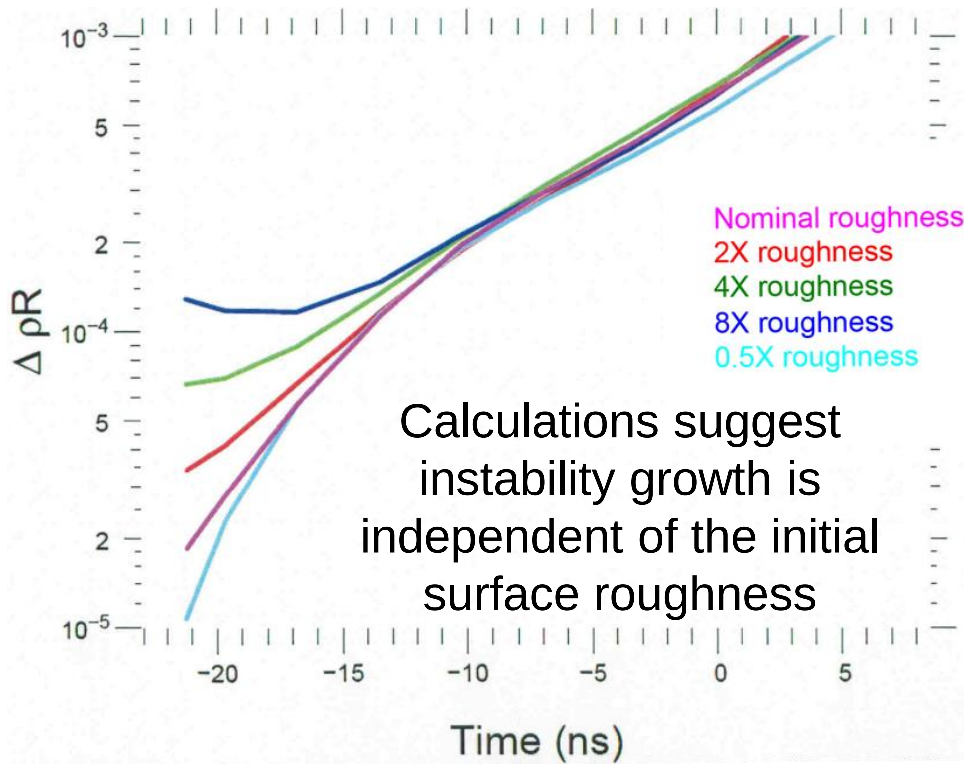


Constant electrical cond.

Nominal

10x thermal conductivity

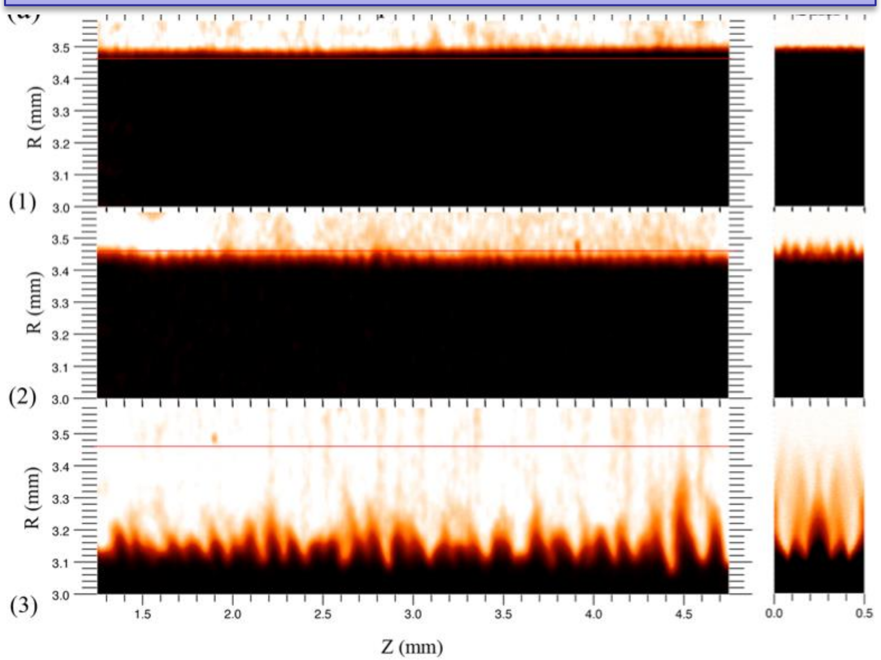


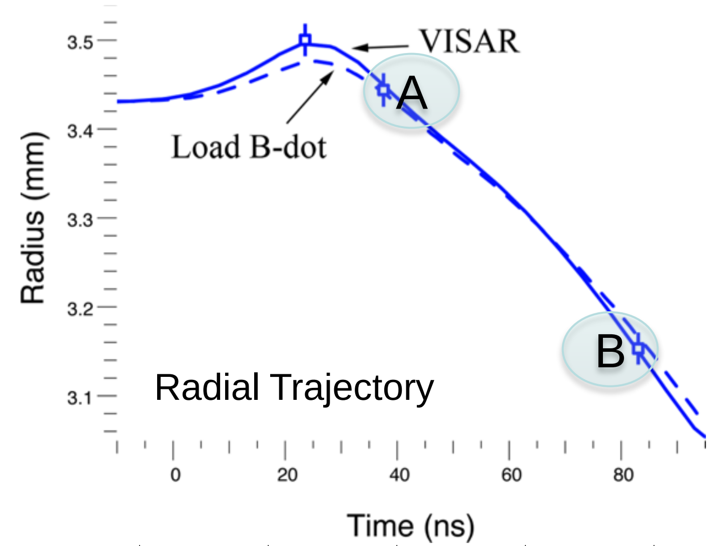


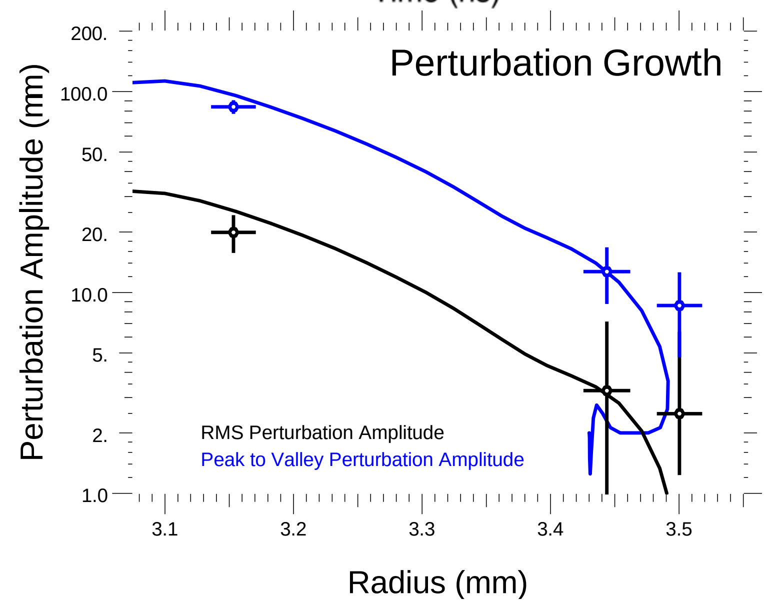
Temperature perturbations give rise to pressure variations which eventually redistribute mass

Comparisons between our modeling and experimental instability growth in solid Al liners are promising—the perturbation growth is larger than expected from MRT alone

Experimental (left) & simulated (right) radiographs





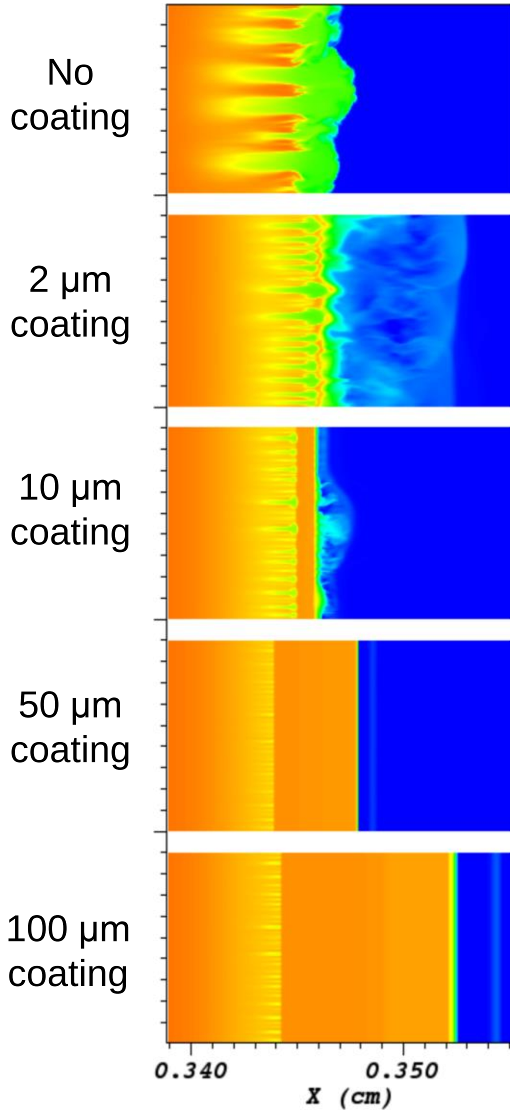


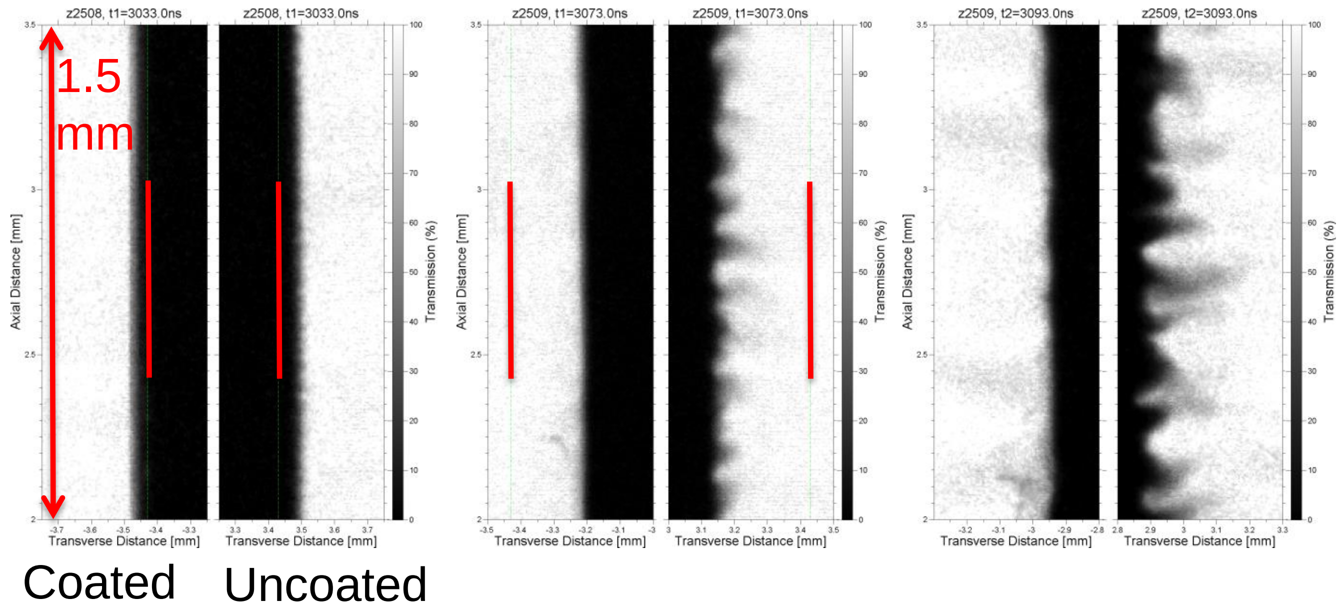
Perturbation Growth Comparison

Time	Est. MRT (λ=100 μm)	$h=0.06Agt^2$	Observed
A	0.36 μm	6.2 μm	13 ± 7 μm
B	24 μm	41 μm	80 ± 7 μm

*K.J. Peterson *et al.*, Phys. Plasmas (2012); K.J. Peterson *et al.*, Phys. Plasmas 20, 056305 (2013).

Simulations predicted that we could mitigate the impact of the electrothermal instability by tamping out the density variations—this was confirmed experimentally

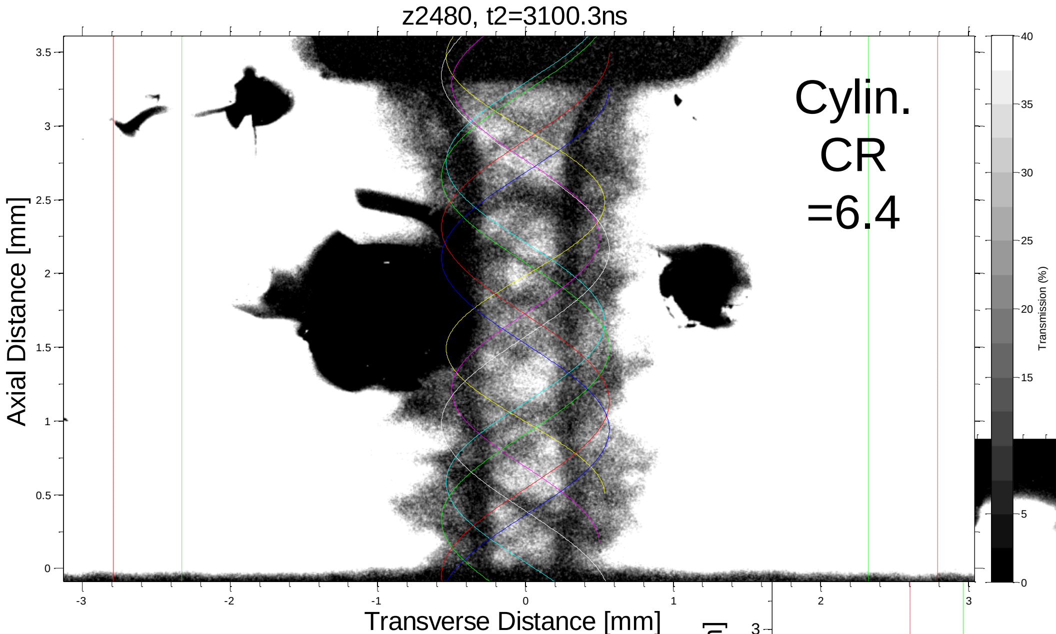


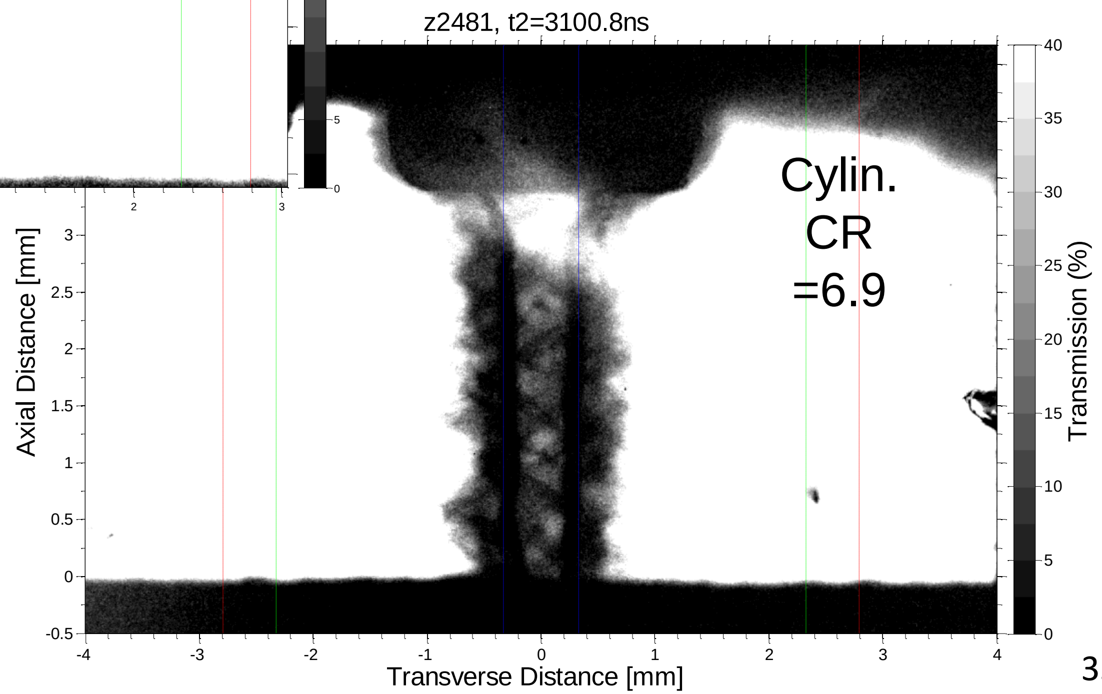


- No ETI growth in plastic coating
  - Carries very little current
  - Theoretically ETI Stable (resistivity decreases with increasing temperature)
- Coating does not appear to affect linear ETI growth of temperature perturbations, but it does significantly tamp down the mass redistribution

K.J. Peterson *et al.*, manuscript in preparation

Though the opacity of the converging liners is significant, it is possible to see the inner boundary adjacent to the fuel, which looks reasonably good



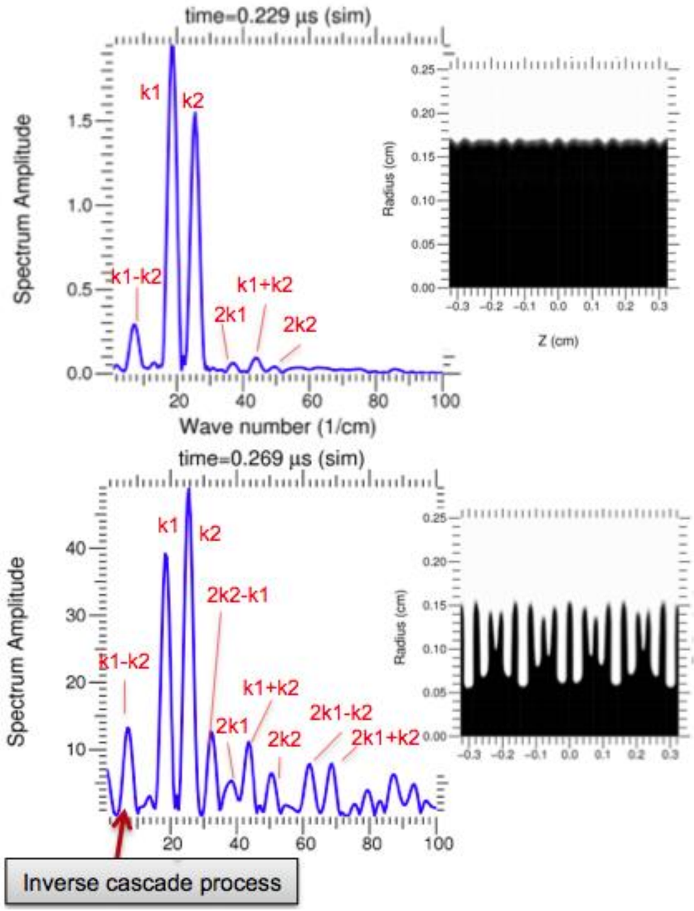


Same images plotted using 0-40% transmission range instead of 0-100%

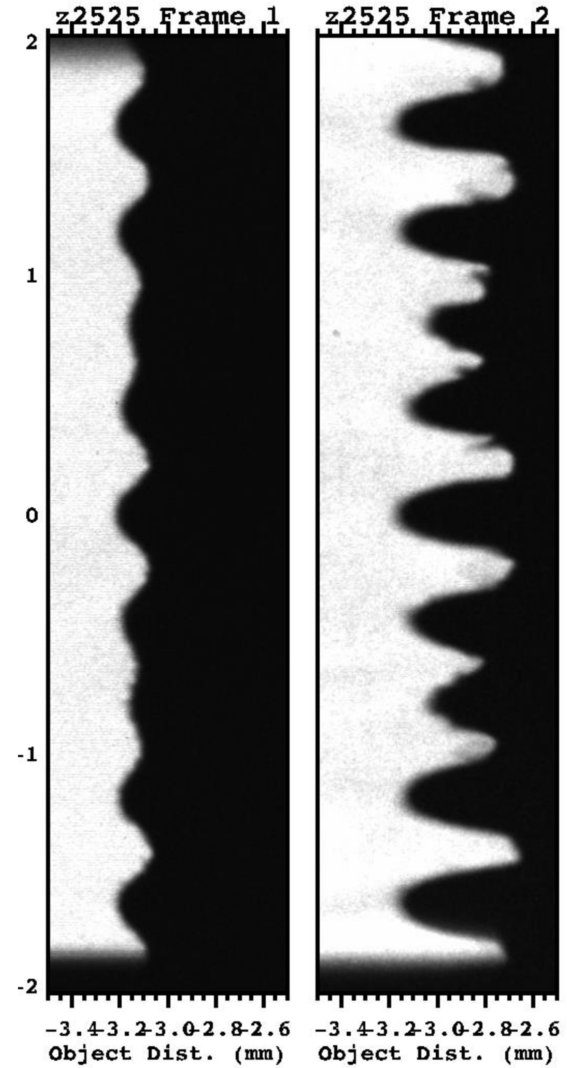
T.J. Awe *et al.*, accepted by Phys. Rev. Lett.

We began studying mode coupling in multi-mode seeded perturbation experiments to test our understanding of multimode MRT instability growth

Two-wavelength structure is machined on outer surface of a cylindrical Al 1100 liner



Additional harmonics are predicted to appear in simulations*

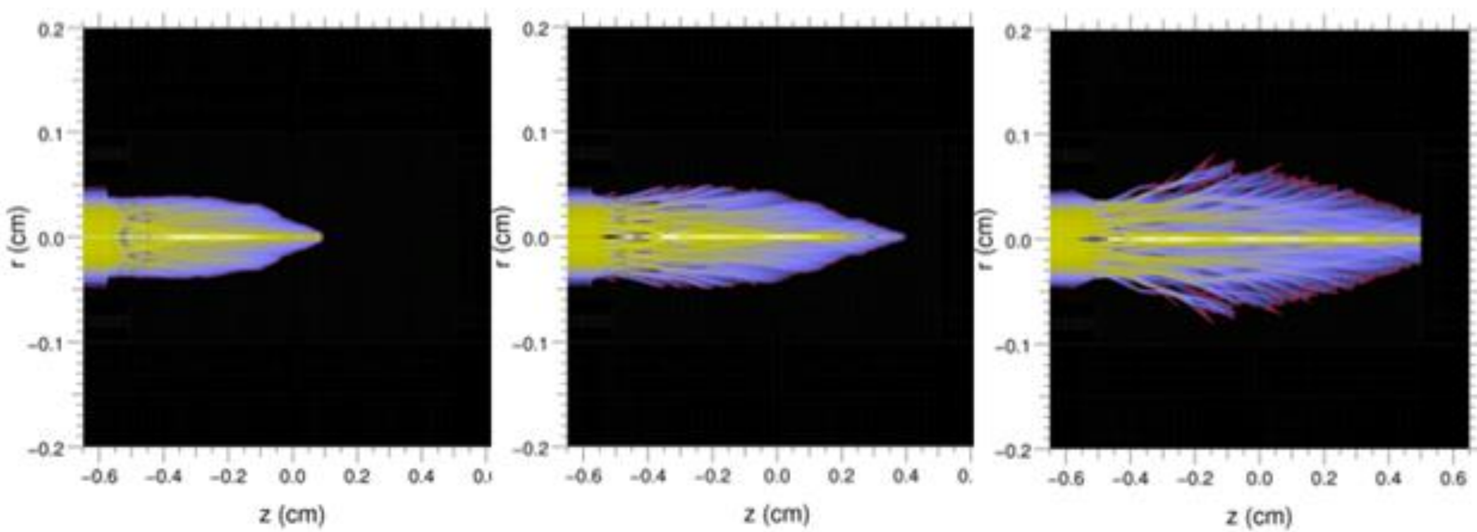


Data show additional short-wavelength features

* Idea first noted by M.R. Douglas *et al.*, Phys. Plasmas 5 (1998).

Z-Beamlet experiments measuring energy deposition are needed because the impact of focal spot quality on filamentation is currently unknown

- Want to absorb 8 kJ of laser energy in ~9 mm long liner filled with ~2 mg/cc D2 without significant energy reaching end of liner
- Lasers propagate in underdense gases in a 'bleaching wave' that travels many times faster than the plasma sound speed
- Intensity variations in beam lead to filamentation which alters the laser energy deposition profile



Hydra sims of laser intensity contours for 2.5 kJ, 1ns, 3ω laser in 2 mg/cc D2 fuel.

The impact of beam quality on laser heating of gasses was demonstrated during preparatory experiments for NIF

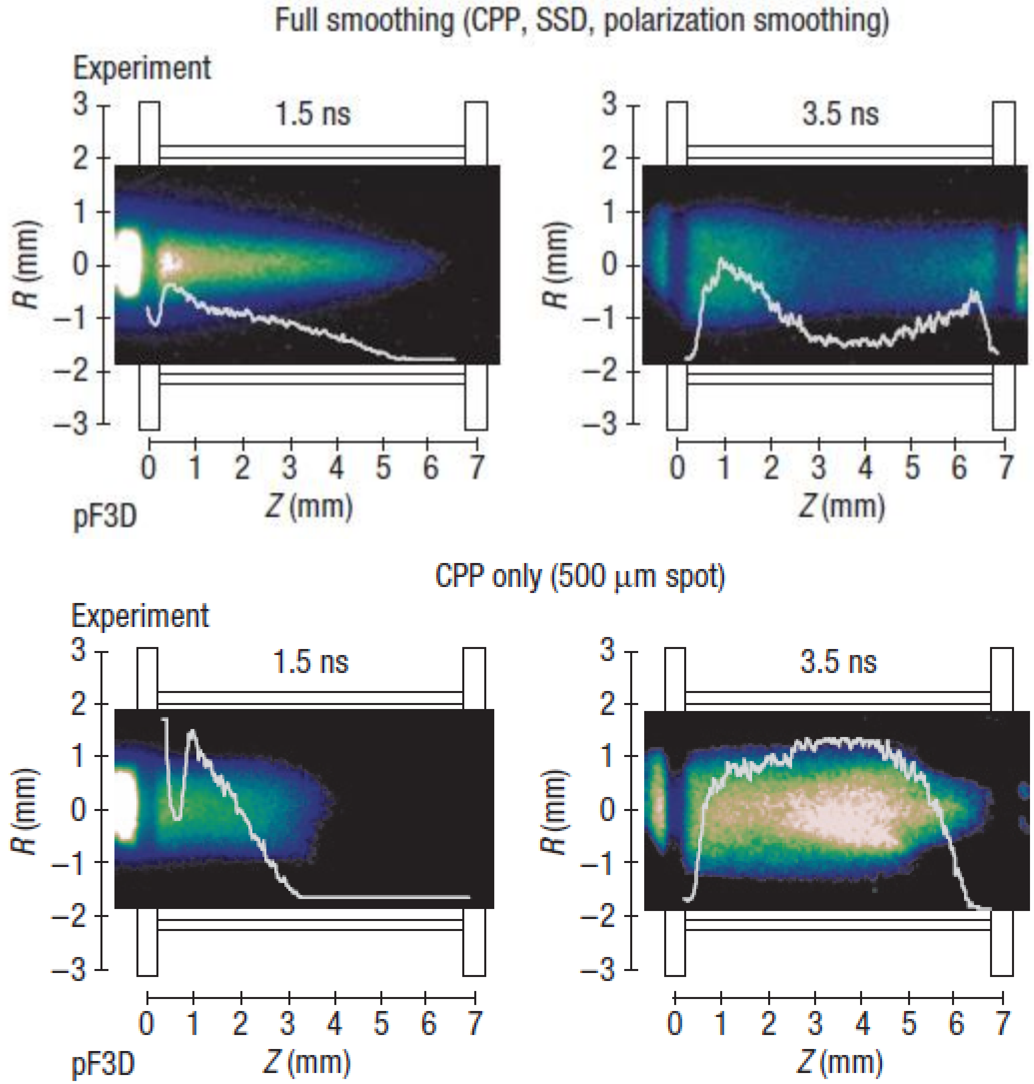
Glenzer et. al., investigated beam propagation through CO2 gas (n_e = 6e20/cc) - relevant to NIF hohlraum

One quadrant of the NIF (16 kJ, 3ω, 3.5 ns, I_0=2e15 W/cm^2) was focused into a 7 mm long gas tube target

Different smoothing resulted in different beam propagation – less smoothing = worse propagation (bad for laser ICF)

We want to absorb as much energy in as shorter distance as possible – want less smoothing?

Also want to have applied B field during experiment



Glenzer et al., Nat. Phys. (2007)

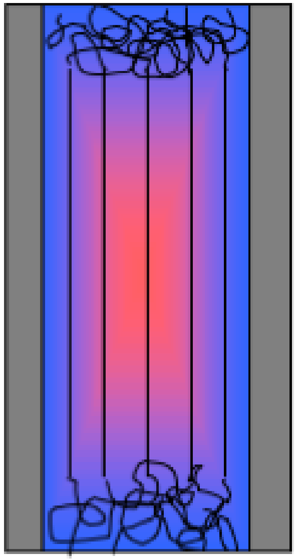
FY15 Experiments on Omega-EP can help us examine the impact of preheating on magnetic field structure

Parallel electron heat flux near cold ends is large and causes distortion of the electron distribution function. This then leads to development of "fire-hose" or "mirror" instabilities if

$$\beta > \left(\frac{n v_{Te} T_e}{q_{||}} \right)^2$$

where $q_{//}$ is axial heat flux. Is satisfied at the distance ~ $L/5$ near each end.

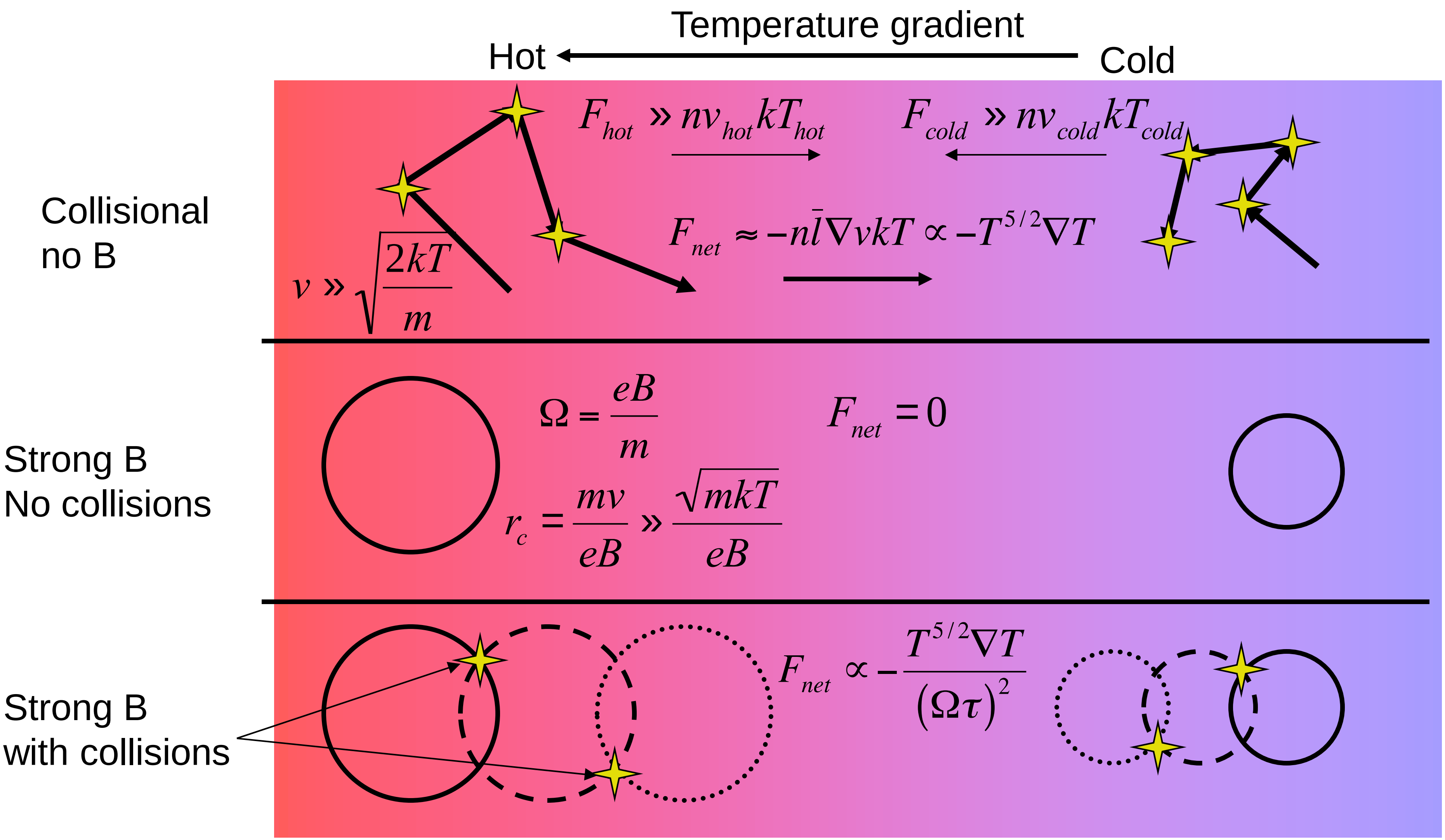
Tangled field is good for suppressing the axial heat loss.



- Detailed estimates suggest that conditions achievable using existing Omega-EP capabilities are nearly ideal for diagnosing existence of tangled field lines using proton radiography*

* D.D. Ryutov (LLNL), 7/16/13 seminar

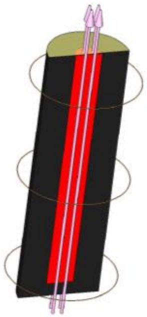
The presence of a magnetic field can strongly affect transport properties, e.g. heat conduction



Energetic particles (e.g., alpha particles) can also be strongly affected by magnetic fields

Simple scalings for a cylindrical implosion apply

Let $R_0 / R_f \equiv CR$ then for high magnetic Reynolds number



$B_{Zf}R_f^2 \sim B_{Z0}R_0^2 \Rightarrow B_{Zf} \sim CR^2 B_{Z0}$ Implies convergences of ~ 20-30 for desired B’s

For an implosion slow compared to the sound speed in the preheated gas (but fast enough that radiative losses are negligible) :

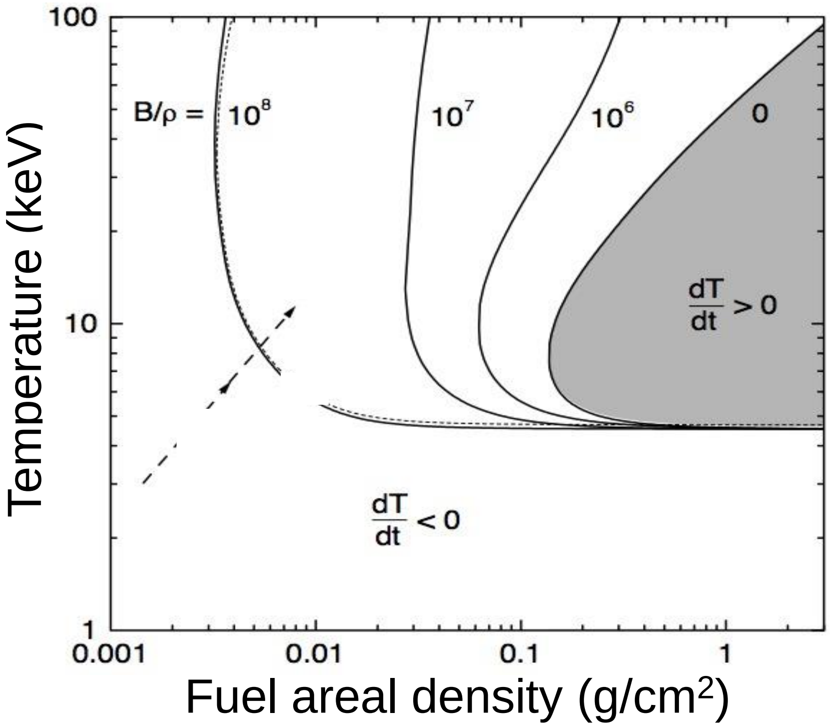
$T \sim T_0 \left(\frac{\rho}{\rho_0}\right)^{2/3} \sim T_0 CR^{4/3}$ Implies T_0 of a few hundred eV for fusion temperatures

Axial α-trapping with open field lines requires $\rho\Delta z > 0.5 g/cm^2$

Implies a final density of ~ 1g/cc

A large, embedded magnetic field significantly expands the space for fusion self heating

*Basko et al. *Nuc. Fusion* 40, 59 (2000)



Even in non-optimal field-line geometry magnetic fields have had a positive impact on capsule implosions:
P.-Y. Chang *et al.*, Phys. Rev. Lett. (2011)

The □r needed for ignition can be significantly reduced by the presence of a strong magnetic field

- Inhibits electron conduction
- Enhances confinement of α particles

Lower □r means low densities are needed (~1 g/cc << 100g/cc)

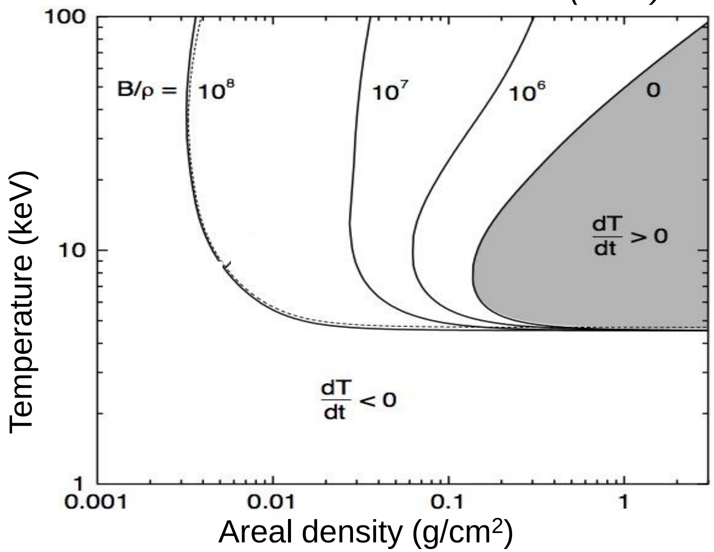
Pressure required for ignition can be significantly reduced to ~5 Gbar
(<< 500 Gbar for hotspot ignition)

Large values of B/□ are needed and therefore large values of B are needed.

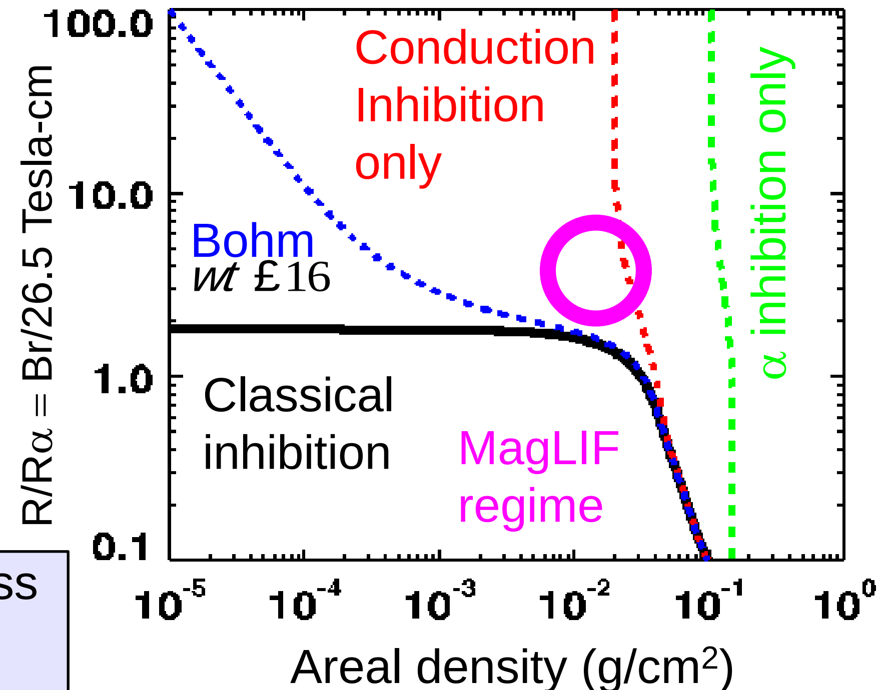
B~ 50-150 Megagauss >> B_0 -> flux compression is needed

Fuel magnetization increases the ignition space (regime where cold fuel can be heated for high gain); the required minimum fuel ρr is replaced with a minimum Br

*Basko et al. Nuc. Fusion (2000)



T=10 keV



Ignition: alpha particle deposition in excess of losses

$$P_a \mu (r r)^2 q^{2.6} f_a$$

f_a,the fraction of the α energy deposited in the fuel increases with either B or ρr

$$P_{Brem} \mu (r r)^2 q^{1/2}$$

Conduction losses are important for small $r r$

$$P_{ce} \mu q^{7/2} F_e (q, B/r)$$

In the limit of large B/r

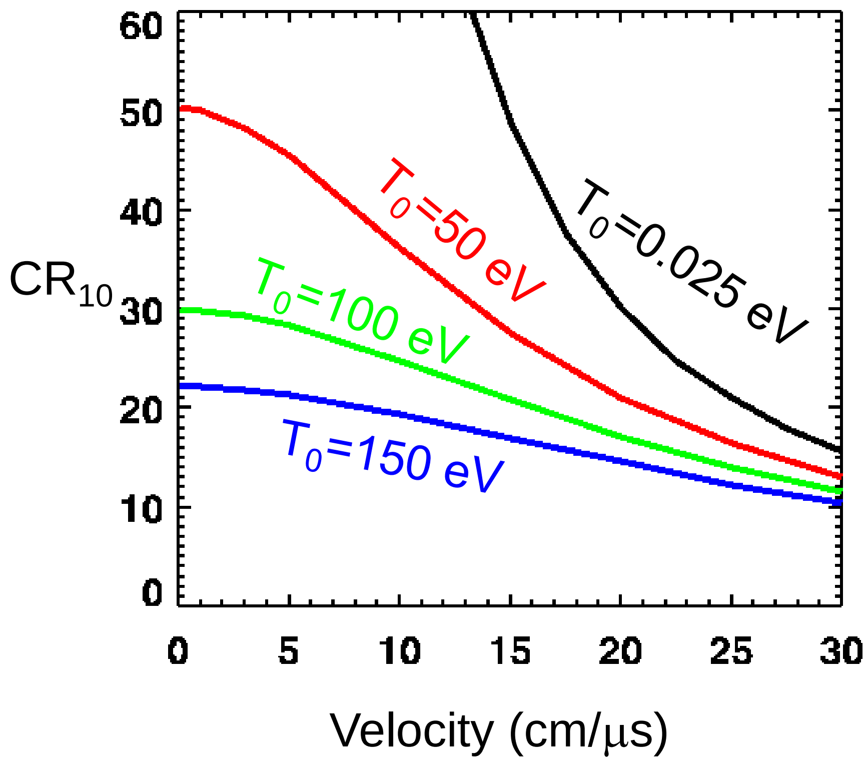
$$F_e (q, B/r) \mu q^{-3} (B/r)^{-2}$$

Axial α-trapping requires closed field lines or moderately high fuel density so that

$$\rho \Delta z > 0.5 g/cm^2$$

Preheating the fusion fuel can reduce the velocity and convergence requirements for liner implosions

Lasnex simulation with constant velocity



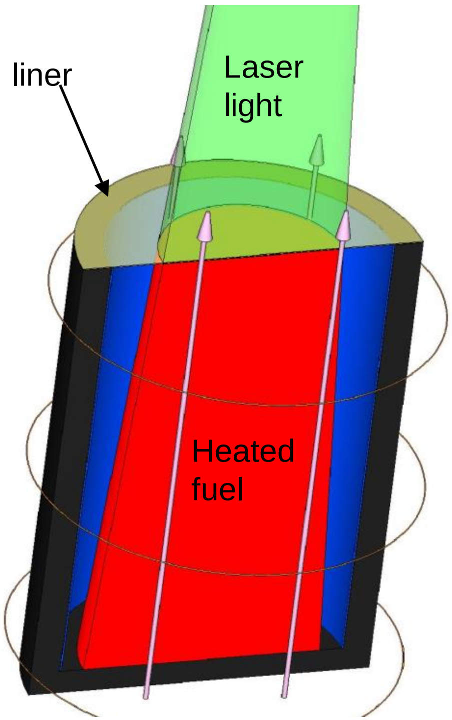
CR_{10} = Convergence Ratio (R_0/R_f) needed to obtain 10 keV (ignition) with no radiation losses or conductivity

Fuel can be heated to ignition temperature with modest Convergence Ratio when the initial adiabat is large

- adiabat set by implosion velocity (shock) or
- alternatively by fuel preheat in addition to a shock

Preheating the fusion fuel to ~150 eV can allow low-velocity, low-convergence implosions to reach ignition and burn

The Z-Beamlet laser is suitable for preheating the fuel on Z experiments



Conditions for heating of DT gas

The critical density for green light is 17 mg/cc in DT

…initial gas density is 2-3 mg/cc implies absorption by inverse bremsstrahlung

The gas can be held in place by a thin plastic foil

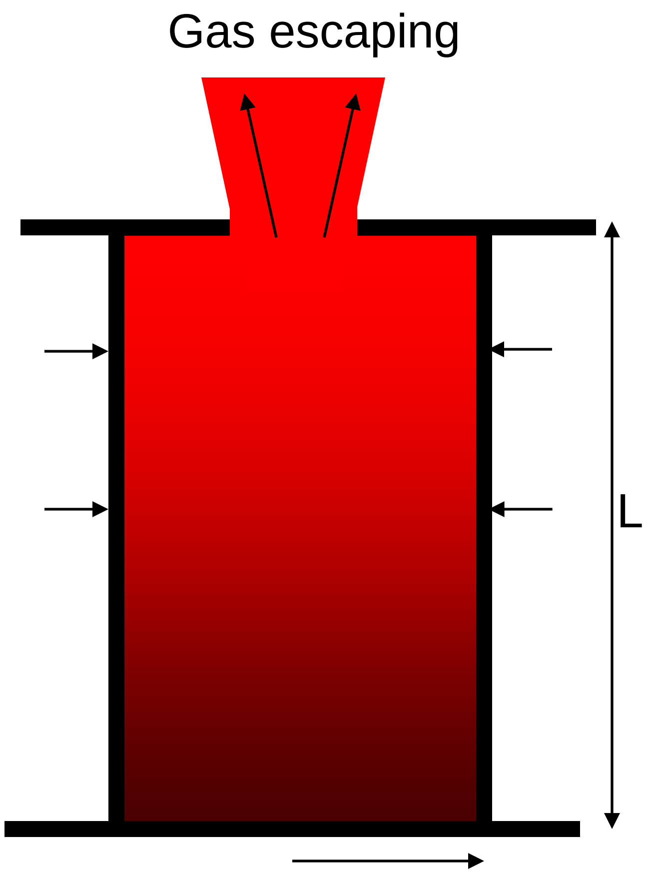
…a 1 μ window will have less areal density than the gas

$$E_{laser} = \pi r^2 L \rho C_V \theta \qquad C_V \approx 1.2x10^8 J/g/keV$$

The total laser energy is modest

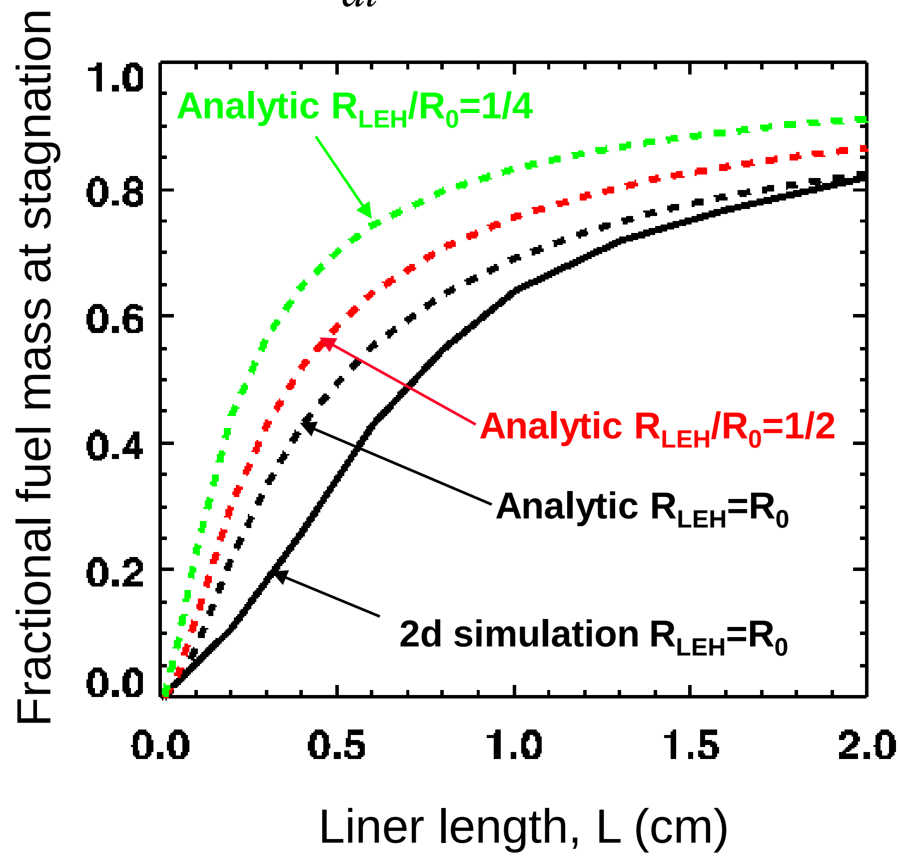
$$E_{laser} \approx 3.4\left(\frac{r}{0.3cm}\right)^2\left(\frac{L}{1cm}\right)\left(\frac{\rho_0}{1mg/cc}\right)\left(\frac{\theta}{0.1keV}\right)kJ$$

The loss of fuel through the laser entrance hole should be manageable



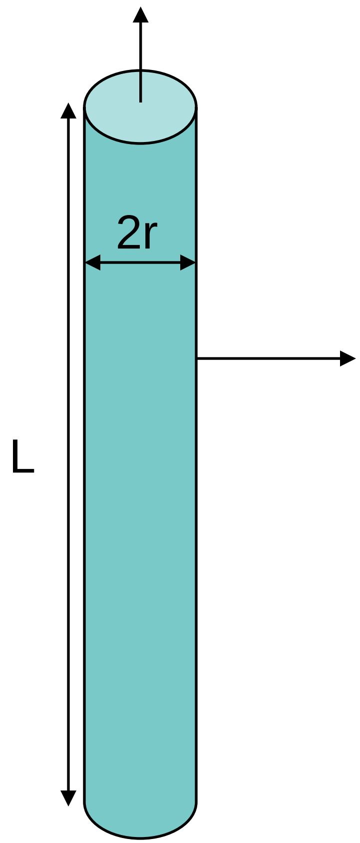
$$r(t) \sim r_0\left[1 - \left(t/t_P\right)^{5/3}\right]$$

$$\frac{dM}{dt} \approx 0.31 c_{s0} \rho_0 \pi r_{LEH}^2$$



Axial thermal losses should be acceptable

Axial loss $L_{axial} = C\theta^{7/2}\left(A = 2\pi r^2\right)\left(\nabla\theta \sim \theta/L\right)$



Radial loss $L_{rad} = C\theta^{7/2}\left(A = 2\pi r L\right)\left(\nabla\theta \sim \theta/r\right)$

$$L_{rad}/L_{axial} = \left(L/r\right)^2 \sim \left(0.5/.01\right)^2 = 2500$$

Axial losses are addressed with fully integrated simulations

MagLIF benefits from short implosion times and is robust to mix due to low Z liner

The optimal fuel density is determined by the balance between PdV heating and Bremstrahlung radiation losses

$$\rho_{final} \approx \left(\frac{100ns}{t_{imp}}\right) g/cc$$

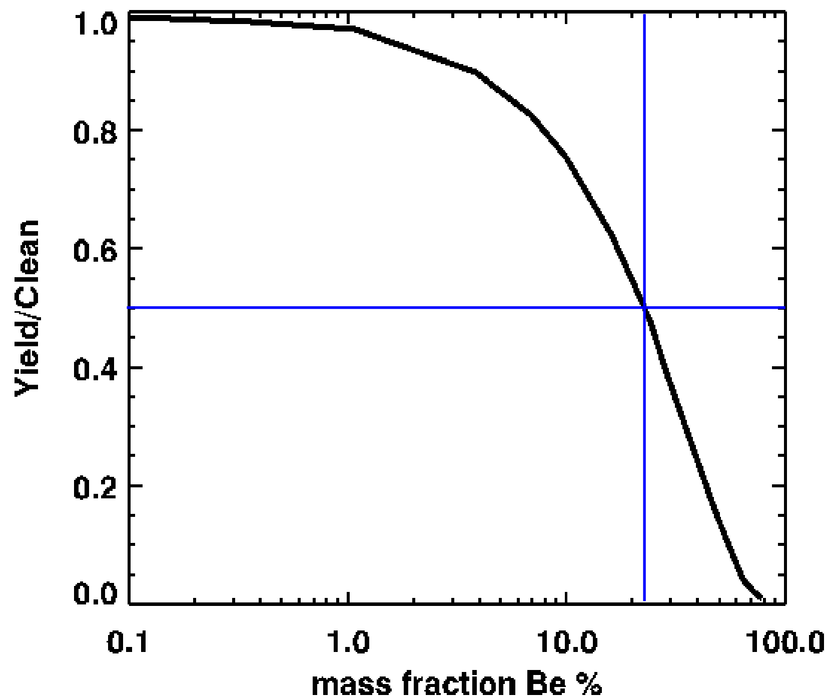
•purely axial fields can be used on Z, since $\rho\Delta z > 0.5$ for small Δz

The preheat energy is roughly proportional to the implosion time

•Fuel preheat requires < 10 kJ for Z (τ_{imp} = 100 ns)

•Preheat feasible with a laser

20% mix degrades the yield by only 50%



The Nernst term has a significant effect on profiles and the yield